A R T I S T S ' A R T I C L E

Modeling the Emergence of Complexity: Complex Systems, the Origin of Life and Interactive On-Line Art

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A B S T R A C T

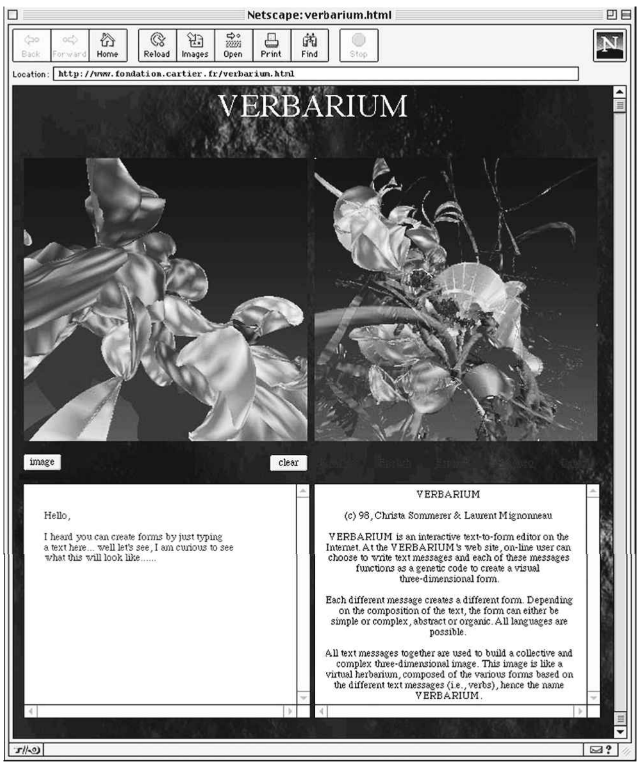
The origin of this paper lies in the fundamental question of how complexity arose in the course of evolution and how one might construct an artistic interactive system to model and simulate this emergence of complexity. Relying on the idea that interaction and communication between entities of a system drive the emergence of structures that are more complex than the mere parts of that system, the authors propose to apply principles of complex system theory to the creation of *VERBARIUM*, an interactive, computer-generated and audience-participatory artwork on the Internet, and to test whether complexity can emerge within this system.

The Internet seems especially suited to interactions and transformations of data. Internet users can be considered entities or particles who transmit information (e.g. written texts or images). As these data or entities are transferred from location to location they could, in principle, change in status and value. One could imagine a system that could increase its internal complexity as more and more users interact with its information. Just like a genetic string or "meme" as described by Susan Blackmore and Richard Dawkins [1], these strings of information would change and mutate as they were transmitted by the users; they eventually could create an interconnected system that, similar to the models presented by Stuart Kauffman [2], features a phase transition toward more complex structures. Based on these considerations, we propose in *VERBARIUM* a prototype system for modeling a complex system for the Internet; we also introduce its construction principles and translation mechanisms and analyze how the data it produces have changed over time.

Conceptual Objective

The aim of the research presented here is to construct an Internet-based interactive artwork that applies and tests principles of complex-system 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 studies simple subsystems as they increase in complexity. Such increases in complexity can take place as phase transitions, when particles in a network switch one another on or off to catalyze or inhibit one another's production. There are various definitions and qualities that characterize complex systems, and this paper proposes to test whether some of these principles can be applied to 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 would be transformed, creating an interconnected, open-ended system featuring phase transitions toward more complex structures. Before investigating how our prototype system was built, we present a short summary of the theories that ground this research proposal.

Fig. 1. Screenshot of the VERBARIUM web site at the Cartier Foundation in Paris, 1999. (© Christa Sommerer and Laurent Mignonneau) <http://www.fondation.cartier.fr/verbarium.html>.



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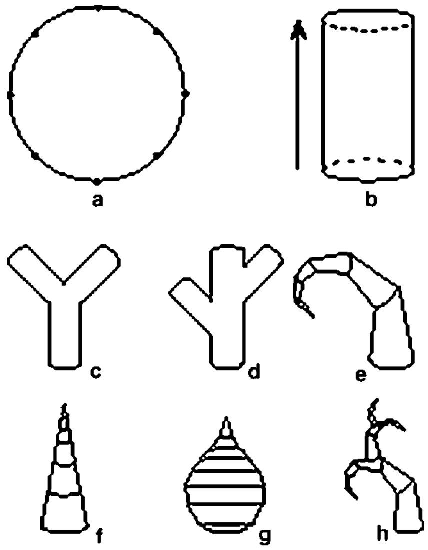

Fig. 2. An example of *VERBARIUM*'s growth structures.

ORIGIN OF LIFE THEORIES

The search for "laws of form" that explain the patterns of order and complexity seen in nature has intrigued researchers and philosophers since the Age of Enlightenment. These researchers have included such famous scholars as William Bateson [3], Richard Owen [4], Hans Driesch [5], D'Arcy Wentworth Thompson [6] and Conrad Waddington [7]. 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 [8] and Neo-Darwinist Richard Dawkins [9]. While 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 history and basically involves two opposing views: the Aristotelian and the Platonic. These two views of the natural world have dominated science over the past two millennia, as described by Roger Lewin [10]. Herrick Baltscheffsky 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 [11].

Speculation on how life on Earth might have originated has a long history, perhaps as long as the history of humanity. The widely accepted hypothesis that life originated from chemical processes derives largely from the 1924 work of Russian biochemist Alexander I. Oparin (translated to English in 1938) [12]. In the 1930s, Oparin and J.B.S. Haldane suggested that life on Earth could have emerged from an early atmosphere filled with such gases as methane, ammonia, hydrogen and water vapor [13]. Oparin and Haldane called this early atmosphere the primordial soup. According to their primordial soup theory, life would have originated in the sea as reactions of these chemical gases were triggered by the energy of lightning, ultraviolet radiation, volcanic heat and natural radioactivity.

In the early 1950s, Stanley Miller [14] of the University of Chicago's chemistry department simulated such a primordial atmosphere and was able to synthesize significant amounts of amino acids, the 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 have been 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. Based on experiments by Sol Spiegelman [15], 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 went a step further by omitting the initial "seed" virus. Eigen succeeded in showing that self-replicating RNA strands could assemble themselves from replicase enzymes alone. 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 interactions "hypercycles." Mutation and competition among these hypercycles finally create prototypes of modern cells, and the earlier chemical evolution is eventually replaced by biological evolution [16]. A similar theory on the origin of life was presented in 1986 by Walter Gilbert [17].

Although the "RNA world" model seems very convincing, the question of where RNA came from in the first place remains open. Leslie Orgel [18], Christian Böhler [19] and P.E. Nielsen [20] found that a peptide nucleic acid, called PNA, could be a precursor form of RNA, because it can act to transcribe its detailed genetic information directly to RNA; therefore, 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 opposed to the "RNA world" theories on the origin of life is the dual-origin theory of A.G. Cairns-Smith [21]. According to Cairns-Smith, the starting point in the early crystallization of life was not "high-tech" carbon but "low-tech" silicon, a component of clay. In this theory, clay has the capacity to grow and reassemble 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 Günter Wächtershäuser [22], the "thioester world" theory of Christian De Duve [23] and the "inorganic pyrophosphate world" or "PPi world" theory of Baltscheffsky. Wächtershäuser proposes a model wherein the 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 Gilbert, Eigen, Böhler, Nielsen and Orgel agree that the RNA world is a first stage of life, Wächtershäuser and others believe that rather primitive entities on mineral surfaces can also be called alive, although he calls them "two-dimensional life." On the other hand, John Maynard Smith and Eörg Szathmáry [24] stress that a living organism needs to possess at minimum a reproduction mechanism, and T. Gánti [25] proposes as a minimum requirement for a living organism that it possess three essential subsystems: a genetic system, a unit that synthesizes the components, and a membrane.

Another major issue in understanding life's origin is to determine the origin of

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. 3. An example of assignment between random functions and design functions.

the genetic translation apparatus and the genetic code as described by Francis Crick in 1968 [26], Crick et al. in 1976 [27] and Carl Woese [28]. Clas Blomberg [29] has claimed 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 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 paper to describe all the other theories on the origin of life in detail; some of them, however, should be mentioned briefly here. These include the "membrane first" theory of Harold Morowitz [30] and the "self-replicating peptide" theory of D.H. Lee et al. [31]. Theories that life was first introduced by meteorites from other planets or stars include the "radiopanspermia" theory of Fred Hoyle and Chandra Wickramasinghe [32] and Carl Chyba's "handedness of the solar system" theory and its influence on the origin of life [33], as well as the "chirality" theories of Yoshihisa Inoue [34].

John Casti notes in his book *Paradigms Regained* that when it comes to defining what it means to be alive, there are as many answers as there are biologists [35]. 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 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" [36].

Complex System Theory

Closely related to the question of how life on earth originated is the question of how complexity arises. Complex system theory has only emerged as a field of research 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. It studies how parts of a system give rise to the collective behaviors of the system and how the system interacts with its environment. Social systems formed (in part) out of people, brains formed out of neurons, molecules formed out of atoms and weather formed out of air currents are all examples of complex systems. The field of complex systems cuts across all traditional disciplines of science, as well as those of engineering, management, and medicine. It focuses on certain questions about parts, wholes and relationships. These questions are relevant to all traditional fields. There are three interrelated approaches to the modern study of complex systems: (1) studying how interactions give rise to patterns of behavior; (2) understanding the ways to describe complex systems; and (3) studying the process of formation of complex systems through pattern formation and evolution [37].

Although there is no exact definition of what a complex system is, there is now an understanding that, when a set of evolving autonomous particles or agents interact, the resulting global system displays emergent collective properties, evolution and critical behavior having universal characteristics. These agents or particles may be complex molecules, cells, living organisms, animal groups, human societies, industrial firms, competing technologies, etc. All of them are aggregates of matter, energy and information that display the following characteristics. They:

- couple to each other
- learn, adapt and organize
- mutate and evolve
- increase in diversity
- react to their neighbors and to external control
- explore their options
- replicate
- organize a hierarchy of higher-order structures.

To find a common principle behind the organizational forces in natural systems is a complex task, and it seems as if there are as many theories as there are theorists. Some of the numerous theories on complex systems are briefly encapsulated in Appendix A (valuable information on the various approaches and definitions of complex system theory are taken from Edmonds [38]).

Properties of Complex Systems

Intrinsically linked to defining complexity is the search for properties of complex systems. Various scholars have undertaken the task of defining these properties. Again, as for the definitions of complexity (see Appendix A), there is no commonly agreed upon "list" of properties that are thought to completely describe it. Some of the commonly mentioned features of complex systems are:

Variety

A complex system is likely to exhibit a great variety in its behavior and properties. Thus variety is an indication of complexity (though not always, as sometimes a very complex system is necessary to maintain equilibrium). Variety can be measured by the simple counting of types, the spread of numerical values or the simple presence of sudden changes.

Dependency

Francis Heylighen [39] suggests that a system's complexity increases when the variety (distinction) and dependency (connection) of parts or aspects increase in at least one of many possible dimensions, including the three ordinary spatial dimensions as well as the dimensions of geometrical structure, spatial scale, time or dynamics, or temporal or dynamical scale. In order to show that complexity has increased overall, it suffices to show that all things being equal, variety

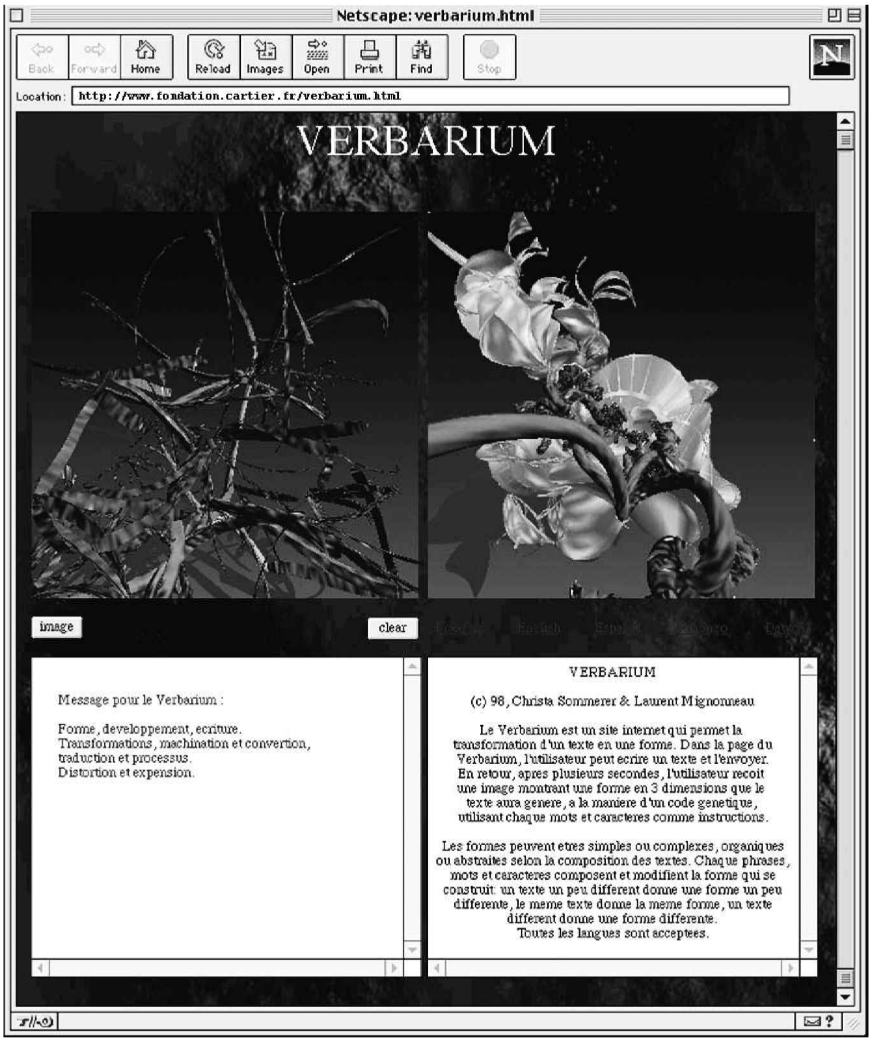

Fig. 4. Screenshot of the *VERBARIUM* web site, 1999. (© Christa Sommerer and Laurent Mignonneau)

and/or connection have increased in at least one dimension.

Irreducibility

Irreducibility is a source of complexity. Randy J. Nelson [40] argues that irreducibility is a key factor in complex systems. Similar approaches include the writings of Philip W. Anderson [41], who points out the importance of size to qualitative behavior, and William Wimsatt [42], who argues that the evolution of multiple and overlapping functions will limit reduction in biology.

Ability to Surprise

The ability to surprise is not possessed by very simple and thus well-understood systems, and consequently has come to be seen as an essential property of complex systems [43].

Symmetry Breaking

Heylighen argues that complexity can be characterized by a lack of symmetry, or "symmetry breaking," in that no part or aspect of a complex entity can provide sufficient information to actually or statistically predict the properties of the other parts. This again connects to the difficulty of modeling associated with complex systems.

Complexity as Relative to the Frame of Reference

Edmonds notes that complexity necessarily depends on the language used to model a system. He argues that effective complexity depends on the framework chosen from which to view/model the system of study. The criticality of scale in the modeling of phenomena has also led R. Badii and A. Politi [44] to focus their characterization of complexity solely on such hierarchical and scaling effects.

Midway between Order and Disorder

Complexity is sometimes posited as a midpoint between order and disorder. Edmonds notes that the definition of complexity as midpoint between order and disorder depends on the level of representation: what seems complex in one representation may seem ordered or disordered in a representation on a different scale.

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 has modeled a hypothetical circuitry of molecules that can switch each other on or off to catalyze or inhibit one of their number's production. As a consequence of this collective and interconnected catalysis or closure, more complex molecules are catalyzed, which again function as catalysts for even more complex molecules. Kauffman argues that, given that a critical molecular diversity of molecules has appeared, life can occur as catalytic closure itself crystallizes. The poised state between stability and flexibility is commonly referred to as the "edge of chaos."

Life at the Edge of Chaos

Christopher Langton [45] and Norman Packard, the scientists who coined the term "life at the edge of chaos," were two of the first to describe the idea of complex patterns. They discovered that in a simulation of cellular automata there exists a transitional region that separates the domains of chaos and order. Cellular automata were invented in the 1950s by John Von Neumann [46]. 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 behavior of cellular automata, they found that although cellular automata obey simple rules of interaction of the type described by Stephen Wolfram [47], 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 typical of complex systems. Langton and Packard's automata indeed show a kind of phase transition between three stages. Langton and Packard hypothesized that the third state, having the highest level of communication, is also the optimal state for adaptation and change and in fact would provide maxi-

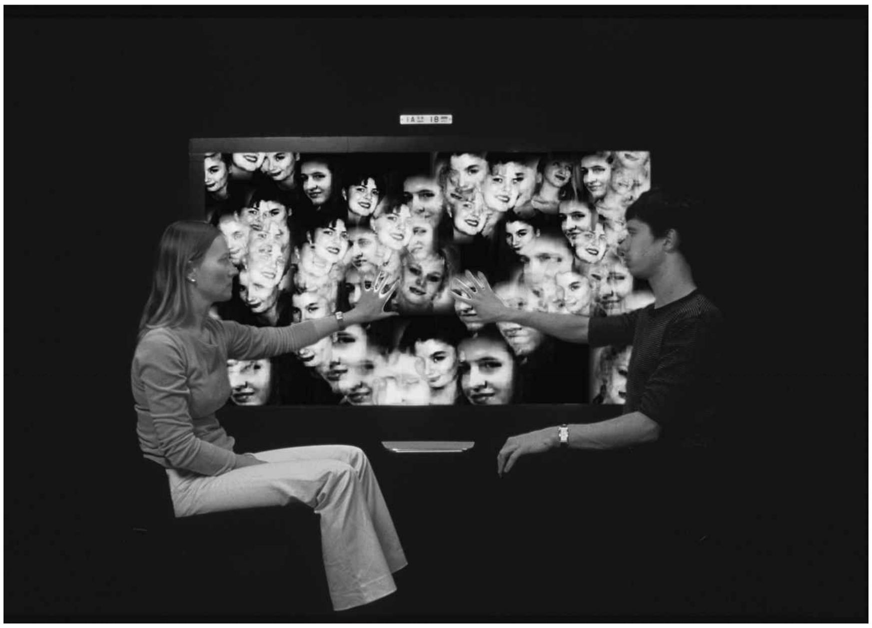

Fig. 5. Installation view of *Riding the Net*, 1999–2000. Two users communicate with each other, and their conversation downloads images and sounds from the Internet. (© Christa Sommerer, Laurent Mignonneau and Roberto Lopez-Gulliver. Developed at ATR MIC Labs, Japan.)

mum opportunities for the system to evolve dynamic strategies of survival. They further suggested that this stage is an attractor for evolving systems. Subsequently, they named the transition phase of this third stage "life at the edge of chaos" [48].

Other researchers at the Santa Fe Institute have extended the idea of life found in this transition phase and applied it to chemistry. In 1992, Walter Fontana developed a logical calculus for exploring the emergence of catalytic closure in networks of polymers [49]. A related approach is seen in the models of physicist Per Bak [50], 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.

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," in which 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 commonly hypothesized that these models could indeed function to explain the emergence of life and complexity in nature. Kauffman's and Langton's concept of phase transition is not the only model for creating complexity; many other approaches are currently being discussed on-line at <http://www.comdig.org> and <http://necsi.org/> and in print by Yaneer Bar-Yam [51].

VERBARIUM: Modeling the Emergence of Complexity for Interactive On-Line Art

Based on the objective to model an interactive on-line artwork that can increase in complexity as users interact with it and on the literature on origin of life and complex system theories, we developed, in 1999, a prototype to model a complex system for the Internet [52].

Artists have been working with the potential of user interaction on the Internet over the past several years. Pioneering artworks include those by Toshihiro Anzai [53], Masaki Fujihata [54], Amerika [55] and Goldberg [56]. The on-line exhibition Net-Condition, at the ZKM Center in Karlsruhe, Germany, provides a good overview of this work [57]. While many of the above works feature a significant amount of user interaction, their main objective does not seem to be that of modeling complexity, as described in the preceding section of this paper.

Our system, called *VERBARIUM,* is an interactive web site [58]. Here users can write e-mail messages that are immediately translated into visual 3D shapes. As the on-line users write various messages to the *VERBARIUM* web site, the messages are translated by our in-house text-to-form editor into various 3D shapes. These shapes are accumulated into image structures that become more complex than the initial input elements. We anticipate that as more users participate, increasingly complex image structures will emerge over time.

VERBARIUM System Overview

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 3D shapes in real time by writing a text message within the interactive text input editor, which appears in the lower-left window of the web site. Within seconds the server receives this message and translates it into a 3D 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 the messages are transformed into shapes and stored in a collective image. An example screenshot of the *VERBARIUM* web site is shown in Fig. 1.

VERBARIUM consists of the following elements:

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

VERBARIUM's Text-to-Form Editor

We have set up a system that uses the simplest possible component for a 3D form that can subsequently model and assemble more complex structures. The simplest possible form we constructed is a ring composed of eight vertices. This ring can be extruded in x, y and z axes, and during the extrusion process the rings' vertices can be modified in these 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, create diverse and constantly growing structures, such as those shown in Fig. 2.

Figure 2a shows the basic ring with 8 vertices, and Fig. 2b shows an extruded

Table 1. *VERBARIUM*'s design function table.

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 × 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

ring forming a segment. Figures 2c and 2d show branching possibilities, with branches diverging from a single point, called an internodium (2c), or from 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 a design function look-up table (Table 1). These functions are essential for "sculpting" the default ring through modifications of its vertex parameters.

The translation of the actual text characters of the user's e-mail message into design function values is done by assigning ASCII values to each text character according to the standard ASCII table shown in Table 2.

Each text character is translated into an integer. We can now proceed by assigning this integer value to a random seed function *rseed.* In our text example (Fig. 3), the *T* in *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 letters that follow in the text, in this case *h,i,s;* we then assign their ASCII values (104 for *h,* 105 for *i,* 115 for *s*), which 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 number of functions that will be updated. Which of the 50 functions are precisely updated is decided by the following random numbers *rseed(104)* (as there are 50 different functions available, the floats that follow are multiplied by 50 to create integers). Figure 3 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)*.

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 according to the design functions available in the design function table in Table 1.

VERBARIUM's Complexity Potential

Depending on the complexity of the incoming text messages, the 3D 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 3D structure; a structure may look like an organic tree or take a more 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. An example of a form created by a text message in French is shown in Fig. 4.

Conclusions

We have introduced an interactive system for the Internet that enables on-line users to create 3D 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 3D shapes. These shapes can become increasingly complex as users interact with the system. A collective image hosts and integrates all of the incoming messages that have been transformed into 3D 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, we suggest that some of the features of complex systems

Table 2. The ASCII table.

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 ~

can emerge. These features include properties such as variety, dependency and symmetry breaking (as described by Heylighen), irreducibility (as described by Nelson) and ability to surprise (as described by Edmonds). While our prototype system succeeds in modeling some of the features of complex systems, future updates of the systems should include the modeling of genetic exchange of information (text characters) between forms, creating offspring forms through standard genetic crossover and mutation operations as we have used them in the past [59]. The potential benefit of such an extended system will be the expansion of diversity, reactivity to neighbors and to external control, exploration of options, and replication—basically, the remaining features commonly associated with complex adaptive systems, as described by Crutchfield. Another further update of the system should also include the capacity to simultaneously display all messages in the browser's window; this should make it possible for users to retrieve all messages ever sent and to follow the whole evolution of the interaction history.

Outlook and Future Works

Since the first publication of this paper, we have become increasingly interested in how users could interact with existing data structures instead of actually creating these complex data structures by themselves. The Internet nowadays contains more than a billion documents, and the amount of text, image and sound data increases by the minute. One could even argue that the Internet itself is one of the best examples of a complex system. It provides an ideal platform for knowledge discovery, data mining and data retrieval and systems that make use of a dynamic and constantly evolving database. To work with the complexity of the Internet in a bottom-up fashion, we have created an interactive installation called *Riding the Net* [60,61]. This system combines speech-recognition software with Internet search engines to pull images and sounds from the Internet in response to a "real-life" conversation. The images are displayed as a moving stream on a large interactive screen from which participants can "grab" images by touching them and then find out where they came from. As users engage in conversations with each other, the content of their conversations becomes visualized as image and sound streams from the Internet. As the conversations are completely unrestricted and unpredictable and the speech recognition system itself also adds a certain amount of unpredictability, the resulting images and sounds represent a dynamic and complex feedback between the user's input data (such as speech and touch) and the system's internal interpretation (such as images and sound files derived from the Internet). The system clearly finds itself at the midpoint between order and disorder (as described by Edmonds), and the resulting interactions create common features of complex systems such as variety, dependency, irreducibility, symmetry breaking, ability to surprise, expansion of diversity and the reaction to neighbors and to external control. The *Riding the Net* system is shown with two users communicating and interacting with each other in Fig. 5.

Appendix A. Definitions of Complexity

Algorithmic Information Complexity: The KCS Definition. The best-known definition of complexity is the Kolmogorov-Chaitin-Solomonoff (KCS) definition [62], describing Algorithmic Information Complexity (AIC), which places complexity somewhere between order and randomness; that is, complexity increases as *Pmin,* the shortest algorithm that can generate a digit sequence, *S,* increases to the length equal to the sequence to be computed; when the algorithm reaches this incompressibility limit the sequence is defined as random. The KCS definition distinguishes between "highly ordered" and "highly complex" structures.

Hinegardner and Engelberg's Number-of-Parts Definition. Perhaps the simplest measure of complexity is that suggested by R. Hinegardner and H. Engelberg [63]: the number of different parts. Hinegardner and Engelberg's measure evokes "exploded" diagrams of pieces of machinery. They give some indication of complexity, but leave out what is perhaps most important: "organization" and "levels of organization" [64].

Crutchfield's Topological Complexity. The topological complexity described by James Crutchfield [65] is a measure of the size of the minimal computational model (typically a finite automaton of some variety) in the minimal formal language in which it has a finite model. Thus the complexity of the model is "objectivized" not only by considering minimal models but also as related to the fixed hierarchy of formal languages.

Computational Complexity. Computational complexity is now a much-studied area with many formal results [66]. The foundation of complexity theory is the research into computability theory undertaken since the 1930s onward by Alan Turing, Alonzo Church and Stephen Kleene [67], among others. The primary considerations then were the formalization of the notion of a computer (e.g. the Turing machine, Church's lambda calculus) and whether such a computer could solve any mathematical problem.

Descriptive Complexity Theory. In 1969, Ronald Fagin decided to study spectra (the spectrum of a first-order sentence is the set of cardinalities of its finite models) and Asser's problem (1955): "Is the class of spectra closed under complementation?" [68] In 1970, his investigations expanded to generalized spectra (i.e. existential second-order spectra where not all relation symbols are quantified out). Fagin's most important result was probably his characterization of NP as the class of generalized spectra in 1974. Interest in the subject has now exploded, mainly due to the intimate relationship (first hinted at by Fagin) between finite model theory and complexity theory [69]. In fact, there is an established subject area within finite model theory dealing explicitly with this relationship: descriptive complexity theory.

Shannon Entropy. Shannon Entropy [70] can be seen as the difficulty of guessing the content of a message passing down a channel, given the range of possible messages. The idea is that the more difficult it is to guess, the more information a message holds. This concept was not intended as a measure of complexity, but has been used as such by subsequent authors.

Goodman's Complexity. Nelson Goodman [71] has devised an elaborate categorization of extra-logical predicates based on expressiveness. For example, a general predicate is deemed more complex than a symmetric one, as it includes the later as a specific example. Likewise, a three-place predicate is more complex than a two-place one. Goodman builds upon this starting point. The idea is that, when faced with two theories that have equal supporting experimental evidence, one should choose the simpler one using this measure. The complexity of a complex statement is merely the sum of the complexities of its component predicates, regardless of the structure of the statement.

Kemeny's Complexity. In the field of "simplicity," John G. Kemeny [72] attributes an integral measure of complexity to types of extra-logical predicates, on the basis of the logarithm of the number of non-isomorphic finite models that a predicate type has. On the basis of this he assigns to extra-logical predicates a measured complexity ranking that could be used to decide between equally supported theories. This is similar in style and direction to Goodman's measure above.

Horn Complexity and Network Complexity. The Horn complexity of a propositional function is the minimum length of a Horn formula (in its working variables) that defines that function. This was defined by S.O. Aaderaa and Egon Börger [73] as a measure of the logical complexity of Boolean functions. It is polynomially related to network or circuit complexity, which is the minimum number of logical gates needed to implement a logical function [74].

Effective Measure Complexity. Peter Grassberger [75] defines the Effective Measure Complexity (EMC) of a pattern as the asymptotic behavior of the amount of information required to predict the next symbol to the level of granularity. EMC can be seen as the difficulty of predicting the future values of a stationary series, as measured by the size of regular expression of the required model. A similar approach is taken by Badii and Politi.

Number of Inequivalent Descriptions. If a system can be modeled in many different and irreconcilable ways, then we will always have to settle for an incomplete model of that system. In such circumstances, the system may well exhibit behavior that would only be predicted by another model. Thus such systems are fundamentally irreducible. Accordingly, the presence of multiple inequivalent models has been considered by Robert Rosen [76] and Howard Pattee [77] as the key characteristic of complexity. Casti [78] extends this approach and defines complexity as the number of nonequivalent descriptions that an observer can generate for a system with which he or she interacts. The observer must choose a family of descriptions of the system and an equivalence relation among them—the complexity is then the number of equivalence classes the family breaks down into, given the equivalence relation.

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