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Oita, JAPAN

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INTERNATIONAL SYMPOSIUM ON ARTIFICIAL LIFE AND ROBOTICS (AROB)

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and Its Application for Hardware
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PREFACE

Masanori Sugisaka
Chairman of AROB
(Professor, Oita University)

It is my great honor to invite you all to The First International Symposium on Artificial Life and Robotics(AROB 1st), organized by Oita University under the sponsorship of Ministry of Education, Science, Sports, and Culture, Japanese Government and co-sponsored by Santa Fe Institute(SFI), USA and SICE, Japan. This symposium invites you all to discuss development of new technology concerning ALife and Robotics using new devices and technologies such as neurocomputer etc., based on simulation and hardware in the field of Microworld Simulation and Realities in 21st century.

This symposium is also financially supported by not only Ministry of Education but also Oita Prefectural Government, Oita Chamber of Commerce and Industry, and other private companies. Prof. Casti introduced SFI research fields during our discussions on joint research two years ago. This symposium was motivated by the discussions. I'd like to express my sincere thanks for Prof. J. L. Casti and also, S. Fujimura, S. Ueno, SFI Professors and all people who contributed to the symposium. I hope that you all will enjoy staying in Beppu, Oita, profit from AROB 1st, and look forward to meeting you in Beppu.

INTERNATIONAL SOCIETY FOR ARTIFICIAL LIFE AND ROBOTICS (ISAROB)

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The First International Symposium on Artificial Life and Robotics (AROB 1st)

Feb. 18-20, 1996, B-Con Plaza, Beppu, Oita, JAPAN

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J. Casti: Santa Fe Institute(Prof. Technical Univ. of Viena)
C. Langton: Santa Fe Institute
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J. M. Epstein: Santa Fe Institute (The Brookings Institution)
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Would-Be Worlds: Toward a Theory of Complex Systems

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1399 Hyde Park Road
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Abstract

By their very nature, complex systems resist analysis by decomposition. It is just not possible to study, say, the human immune system or a stock market, by breaking it up into individual parts—molecules or traders—and looking at what these parts do in isolation. The very essence of the system lies in the interaction among all its parts, with the overall behavior of the system emerging from these interactions. So by throwing away the interactions, one also throws away any hope of actually understanding the workings of the system. The problem is that until very recently, there was no way of studying these sorts of systems as complete entities, since to do experiments with stock markets, immune systems, rainforest ecosystems and the like was either too expensive, too dangerous or just plain too difficult. But the arrival of cheap, powerful, widespread computing capability over the past decade or so has changed the situation entirely.

This talk will examine the way in which the ability to create surrogate versions of real complex systems inside our computing machines changes the way we do science. In particular, emphasis will be laid upon the idea that these so-called "artificial worlds" play the role of laboratories for complex systems, laboratories that are completely analogous to the more familiar laboratories that have been used by physicists, biologists and chemists for centuries to understand the workings of matter. But now we have laboratories that allow us to explore information instead of matter. And since the ability to do controlled, repeatable experiments is a necessary precondition to the creation of a scientific theory of anything, the argument will be made that for perhaps the first time in history, we are now in a position to realistically think about the creation of a theory of complex systems.

These philosophical points will be illustrated by ongoing work with artificial road-traffic networks, as well as with systems for studying social and cultural phenomena.

1 Introduction

By more-or-less common consensus, Galileo is credited with ushering-in the idea of controlled, repeatable, laboratory experiments for the study of physical systems. And as such experiments are an integral part of the so-called *scientific method,* it's no exaggeration to say that Galileo's work formed a necessary precondition for Newton's creation of a workable *theory* of systems composed of interacting particles, a theory that formed the basis for much of modern theoretical science. But Newton's particle systems are what in today's parlance we would term "simple" systems, since for the most part they are formed of either a very small or a very large number of interacting "agents" (i.e., particles) interacting on the basis of purely local information in accordance with rigid, unvarying rules. Complex systems are different.

Typically, complex systems like a stock market or a road-traffic network involve a medium-sized number of agents (traders or drivers) interacting on the basis of limited, partial information. And, most importantly, these agents are intelligent and adaptive. Their behavior is determined by rules, just like that of planets or molecules. But the agents are ready to change their rules in accordance with new information that comes their way, thus continually adapting to their environment so as to prolong their own survival in the system. At present, there exists no decent mathematical theory of such processes. One part of the argument to be made here is that a major stumbling block in the creation of a theory of complex, adaptive systems has been the lack of ability to do the kind of controlled, repeatable experiments that led to theories of simple systems. The second-half of our argument is that the microsimulations, or "would-be worlds," presented at this meeting constitute nothing less than laboratories for carrying out just such experiments. So for the first time in history, we have the experimental tools with which to begin the creation of a bona fide theory of complex, adaptive systems.

2 Theories, Experiments, and "Big Problems"

To see the role that microsimulations will play in the creation of a theoretical framework for complex systems, it's instructive to examine briefly the history of theory construction for several major areas of modern science.

Typically, a theory of something begins its life with what I'll call a "Big Problem." This is some question about the world of nature or humans that cries out for an answer, and that seems approachable by the concepts and tools of its time. Just to get a feel for what such questions are like, here is a rather eclectic list of Big Problems from a few areas of natural and human affairs:

- *Biology: The Structure of DNA*—What is the geometrical structure of the DNA molecule, and how does this structure lead to the processes of heredity?
- *Astrophysics: The Expanding Universe*—Is the Universe open or closed, i.e., will it continue to expand forever, or will a phase of contraction back to a "Big Crunch" occur?
- *Economics: Equilibrium Prices*—In a pure exchange economy, does there exist a set of prices at which all consumers and suppliers are satisfied, i.e., is there a set of prices for goods in the economy at which the supply and demand are in balance?
- *Physics: Stability of the Solar System*—Does there exist a finite time in the future at which either there will be a planetary collision, or at which some planet attains a velocity great enough to escape the solar system?

So what we have here are four questions about the real world, each of which arises pretty much from opening our eyes and looking around. And each of these questions has given rise to a theoretical framework within which we can at least ask—if not answer—the question. But these theoretical frameworks, be they the theory of knots for studying the geometry of DNA or the fixed-point theories of economics that tell us about prices, have each come about as the outgrowth of experiments with the system of interest. For example, it was only by having access to the x-ray crystallographic studies by Rosalind Franklin that James Watson and Francis Crick were able to uncover the double-helix structure of DNA. Similarly, observations by Edwin Hubble using at the Mount Palomar Observatory showed the expansion of the universe, an empirical fact that has led to current theories of dark matter for answering the question of whether or not this expansion will continue indefinitely.

These examples—and the list could be extended almost indefinitely—illustrate the so-called *scientific method* in action. It consists of four main steps:

→ observation → theory → hypothesis → experiment →

This diagram makes the importance of experimentation evident; in order to test hypotheses suggested by a theory, we must have the ability to perform controlled, repeatable experiments. And this is exactly where the microsimulations possible using today's computing machines enter into our discussion. In contrast to the more familiar laboratories of the chemist, physicist or biologist, which are devoted to exploring the *material* structure of simple systems, the computer-as-a-laboratory is a device by which we can probe the *informational* structure of complex systems. Let me look at this point just a bit further.

3 Information versus Matter

For the past 300 years or more, science has focused on understanding the material structure of systems. This has been evidenced by the primacy of physics as the science par excellence, with its concern for what things are made of. The most basic fact about science in the 21st century will be the replacement of matter by information. What this means is that the central focus will shift from the material composition of systems—what they are—to their functional characteristics—what they do. The ascendancy of fields like artificial intelligence, cognitive science, and now artificial life are just tips of this iceberg.

But to create scientific theories of the functional/informational structure of a system requires employment of a totally different type of laboratory than one filled with retorts, test tubes or bunsen burners. Rather than these labs and their equipment designed to probe the material structure of objects, we now require laboratories that allow us to study the way components of systems are connected, what happens when we add/subtract connections, and in general, experiment with how individual agents interact to create emergent, global behavioral patterns.

Not only are these "information labs" different from their "matter labs" counterparts. There is a further distinction to be made even within the class of information labs. Just as even the most well-equipped chemistry lab will help not one bit in examining the material structure of, say, a frog or a proton, a would-be world designed to explore traders in a financial market will shed little, if any, light on molecular evolution. So let me conclude this short discussion by considering some would-be worlds, each each having its own characteristic sets of questions that it's designed to address.

4 Would-Be Worlds

In the past few years, a number of electronic worlds have been created by researchers associated with the Santa Fe Institute to study the properties of complex, adaptive systems. Let me cite just three such worlds here as prototypical examples of the kind of information laboratory we have been discussing.

- *Tierra*—This world, created by naturalist Tom Ray [1], is populated by binary strings that serve as electronic surrogates for genetic material. As time unfolds, these strings compete with each other for resources, with which they create copies of themselves. New strings are also created by computational counterparts of the real-world processes of mutation and crossover. Over the course of time, the world of *Tierra* displays many of the features associated with evolutionary processes seen in the natural world, and hence can be used as a way of experimenting with such processes—without having to wait millions of years to bring the experiment to a conclusion. But it's important to keep in mind that *Tierra* is not designed to mimic any particular real-world biological process; rather, it is a laboratory within which to study neodarwinian evolution, in general.

- *TRANSIMS*—For the past three years, a team of researchers at the Los Alamos National Laboratory headed by Chris Barrett has built an electronic counterpart of the city of Albuquerque, New Mexico inside their computers. The purpose of this world, which is called *TRANSIMS,* is to provide a testbed for studying the flow of road traffic in an urban area of nearly half a million people. In contrast to *Tierra, TRANSIMS* is explicitly designed to mirror as the real world of Albuquerque as faithfully as possible, or at least to mirror those aspects of the city that are relevant for road-traffic flow. Thus, the simulation contains the entire road traffic network from freeways to back alleys, together with information about where people live and work, as well as demographic information about incomes, children, type of cars and so forth. So here we have a would-be world whose goal is to indeed duplicate as closely as possible a specific real-world situation.

- *Sugarscape*—Somewhere in between *Tierra* and *TRANSIMS* is the would-be world called *Sugarscape,* which was created by Joshua Epstein and Rob Axtell of The Brookings Institution in Washington, DC. This world [2] is designed as a tool by which to study processes of cultural and economic evolution. On the one hand, the assumptions about how individuals behave and the spectrum of possible actions at their disposal is a vast simplification of the possibilities open to real people as they go through everyday life. On the other hand, *Sugarscape* makes fairly realistic assumptions about the things that motivate people to act in the way they do, as well as about how they go about trying to attain their goals. What is of considerable interest is the rich variety of behaviors that emerge from simple rules for individual action, and the uncanny resemblance these emergent behaviors have to what's actually seen in real life.

The main point of bringing up *Tierra, TRANSIMS,* and *Sugarscape* is to emphasize two points: (A) We need different types of would-be worlds to study different sorts of questions, and (B) each of these worlds has the capability of serving as a laboratory within which to test hypotheses about the phenomena they can represent. And, of course, it is this latter property that encourages the view that such computational universes will play the same role for the creation of theories of complex systems that chemistry labs and particle accelerators have played in the creation of scientific theories of simple systems. For a fuller account of the technical, philosophical and theoretical problems surrounding the construction and use of these silicon worlds, see the author's volume [3] which will appear in the fall of 1996.

References

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Artificial Societies and Generative Social Science

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Abstract

What is an *artificial society*? What can such models offer the social sciences in particular? We address these general questions, drawing brief illustrations from the specific artificial society we call "Sugarscape."

1 What is an Artificial Society?

An artificial society is a computer model consisting of (i) a population of autonomous *agents* (ii) a separate *environment* and (iii) *rules* governing the interaction of agents with one another, the interaction of agents with their environment, and the interaction of environmental sites with one another. Let us discuss each of these ingredients in turn.

1.1 Agents

Agents are the "people" of artificial societies. An agent is a data structure--in programming parlance, an "object"--that can change, or "adapt," over time. Each agent has "genetic" attributes, "cultural" attributes, and various operating rules governing its interactions with the environment and with other agents. Genetic attributes are "hard-wired," fixed for the lifetime of the agent. In Sugarscape, an agent's sex, metabolism, and vision, are genetic. Cultural attributes, by contrast, are not hard-wired; they are transmitted "vertically" from parents to children, but then change "horizontally" through contact with other agents. In Sugarscape, individual economic preferences are culturally determined--they can change as agents move around and bump into agents with different tastes. At any time the interacting agents differ in myriad ways--by age, by culture, by wealth, by vision, by economic tastes, by immunocompetence, and so forth: artificial societies are full of diversity.

1.2 Environment

Artificial social life unfolds in an environment. The Sugarscape, as the name suggests, is a landscape of generalized renewable resource (sugar) that agents like to eat; indeed they metabolize sugar and need it to live. An artificial society environment is often spatial, such as a two-dimensional lattice, but can be a more abstract--and dynamic--structure, such as the Internet. The point is that it is an external medium with which the agents interact and over which the agents "navigate."

1.3 Rules

Finally, there are rules of behavior for the agents and the environment. First, there are rules coupling every site of the environment to its neighbors, as in cellular automata. For example, the rate at which sugar regenerates at a feeding site could be a function of the sugar levels at neighboring sites. Second, there are rules coupling the agents to the environment. The simplest movement rule for Sugarscape agents is: *look around as far as your vision permits; find the site richest in sugar; go there and eat the sugar*. Of course, movement under this rule may bring the agent into contact with new neighbors, which brings us to the third set of rules, those governing interagent interactions. In Sugarscape, there are rules governing sex, combat, trade, disease transmission, and cultural transmission between neighbors.

2 Social Structures Emerge

In a typical artificial society experiment, we release an initial population of agents into the simulated environment and watch for *self-organization* into recognizable macroscopic social patterns. The formation of tribes or the emergence of certain stable wealth distributions are examples. Indeed, the defining feature of an artificial society is precisely that *fundamental social structures and group behaviors emerge from the interaction of individual agents operating in artificial environments under simple local rules—rules that place only bounded demands on each agent's information and computational capacity*. The shorthand for this is that we "grow" the collective structures "from the bottom up".

Our Sugarscape model--forthcoming on CD-ROM [1]--integrates population dynamics, migration, combat, trade, cultural transmission, genetics, environmental interactions, immunology, and epidemiology in a spatially distributed artificial society of heterogeneous adaptive agents with limited information, bounded computing capacity, evolving preferences, and other recognizably human attributes and limitations. Our broad aim is to begin the development of a unified evolutionary social science subsuming--and extending--such fields as economics and demography.

The general point, however, is that artificial societies can function as laboratories--CompuTerraria--where we "grow" fundamental social structures *in silico*, thereby *revealing* simple micro-generators of the macro-phenomena of interest. This is a central aim. As social scientists, we are presented with "already emerged" collective phenomena--such as settlement patterns, fertility rates, or wealth distributions--and we seek simple local rules that can generate them. We of course use statistics to test the match between the true, observed, structures and the ones we grow; but the ability to grow them—greatly facilitated by modern object-oriented programming—is what is new. Indeed, it holds out the prospect of a new kind of social science.

3 Generative Social Science

In particular, from an epistemological standpoint, what "sort of science" are we doing when we build artificial societies? Clearly, agent based social science does not seem to be deductive or inductive in the usual senses. But then what is it? We think *generative* is an appropriate term. The aim is to provide initial microspecifications (initial agents, environments, and rules) that are *sufficient to generate* the macrostructures of interest. We consider a given macrostructure to be "explained" by a given microspecification when the latter's generative sufficiency has been established. We interpret the question "can you explain it?" as asking "can you grow it?" In effect, we are proposing a generative program for the social sciences and see "the artificial society" as its principal scientific instrument.

References

[1] Joshua M. Epstein and Robert Axtell, *Growing Artificial Societies: Social Science from the Bottom Up*, The Brookings Institution and MIT Press, 1996

[2] On questions of validation, see Robert L. Axtell and Joshua M. Epstein, "Agent-Based Modeling: Understanding Our Creations," *The Bulletin of the Santa Fe Institute*, Winter 1994, Vol. 9, No. 2.