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(AROB) 1st

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

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ON
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(AROB)

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Dr. Y.Tokura(ATR, JAPAN)
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Prof. T.Nagata(Kyushu University, JAPAN)
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Artificial Brains
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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.

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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

TECHNICAL PAPER INDEX

Plenary Session : Invited Talks

The Science and the Surprise of Artificial Worlds
J. L. Casti(Santa Fe Institute, USA, Technical University of Viena)

The SWARM simulation system for modelling complex systems
C. G. Langton(Santa Fe Institute, Director, USA)

Numerical Analysis of the State of Mind
T. Musha(Brain Function Laboratory, Inc., President and Keio University, Special Invited Professor, Japan)

Evolution of Digital Organisms
T. Ray(ATR Human Information Processing Research Laboratories, Japan and USA)

Insect-Model Based Microrobot
H. Miura(University of Tokyo, Japan)

The Economy as an Ocean of Co-Evolving Beliefs
W. B. Arthur (Santa Fe Institute, Dean of Economics, Stanford University, USA)

Growing Artificial Societies: The Sugarscope Model
J. M. Epstein(Santa Fe Institute, The Brookings Institution, USA)

Dynamical Hierarchies
S. Rasmussen (Santa Fe Institute, Los Alamos National Laboratory, USA)

Session A1: Artificial Life

A1-1 *Computational Approach to Consciousness: Continuous Self-Monitoring, Identification, Evaluation and Decision*
Y.Ishida(Nara Institute of Science and Technology, Japan)

A1-2 *A Robot with a Personality-a fuzzy adaptive model of emotion and personality for an autonomous robot-*
K. H. Ho, N. Ohnishi(The Institute of Phisical and Chemical Research(RIKEN), Japan)

A1-3 *Study of Loop Structure on Abstract Rewriting System and its Application to Artificial Life*
Y. Suzuki, S. Tsumoto, H. Tanaka
(Tokyo Medical and Dental University, Japan)

A1-4 *An Advanced Simulation Scheme for Electric Railway Power Systems Based on Artificial Life Approach*
T. Jinzenji, M. Sasaki(Tohoku University, Japan)

A1-5 *Adaptive Block Dividing and Quantization for Image Compression using Artificial Breeding*
H. Hiramatsu, S. Kitamura(Kobe University, Japan)
Y. Kurematsu(College of Industry Technology, Japan)

Session A2: Neural Network

A2-1 *Human Type Controller Using Combined Neurons of Different Type*
T. D. Eom, J. J. Lee(Korea Advanced Institute of Science and Technology(KAIST), Korea)

A2-2 *Neurocomputer Control for Tracking of Moving Objects*
M. Sugisaka(Oita University, Japan)

A2-3 *Reinforcement Learning of Dynamic Behavior by using Recurrent Neural Networks*
A. Onat, H. Kita, Y. Nishikawa(Kyoto University, Japan)

A2-4 *Pattern Recognition Via Neurocomputer*
M. Sugisaka(Oita University, Japan)

A2-5 *Classification of Landsat TM Data Using Neural Network Approaches*
Y. Kawata, Y. Yashima(Kanazawa Institute of Technology, Japan)

A2-6 *Fault Diagnosis of Logical Circuit by use of Pseudorandom signal and Neural Network*
H. Kashiwagi, M. Sakata(Kumamoto University, Japan)

Session B1: Robotics-General-

B1-1 *A Language for Describing Motions of Mechatronic Systems :A Nonlinear Position-Dependent Circuit Theory*
S. Arimoto(University of Tokyo, Japan)

B1-2 *Aspects of Non-Cartesian Robotics*
T. Gomi(Applied AI Systems, Inc., Canada)

B1-3 *Evaluation of Robust Control by Universal Learning Network*
M. Ohbayashi, K. Hirasawa, J. Murata (Kyusyu University, Japan)

B1-4 *Cooperative Behavior of Interacting Robots*
K. Sugawara, M. Sano, Y. Sawada (Tohoku University, Japan)

B1-5 *A Step Toward Human-Robot Cooperative System*
M. Ishii, H. Saita(Fukuoka Institute of Technology, Japan)

B1-6 *A Method of Gait Coordination of Hexapod Robots Using Mutual-Coupled Immune Networks*
A. Ishiguro, S. Kuboshiki, S. Ichikawa, Y. Uchikawa
(Nagoya University, Japan)

Session B2: Genetic Algorithm

Chair: J. J. Lee(KAIST, Korea)

B2-1 *A Control Design Method of Robotic System by Genetic Algorithm*
T. Tsuji, T. Hachino(Kyusyu Institute of Technology, Japan)
R. Oguro, N. Umeda(YASUKAWA Electric MFG Co., LTD, Japan)
H. Takata(Kagoshima University, Japan)

B2-2 *Robot Path Planning through Some Places by Genetic Programming*
H. Yamamoto(Wakayama University, Japan)

B2-3 *A Local Motion Planner for Unicycle-like Vehicles: Guaranteeing the Collsion Avoidance Even in the Unknown Environment*
S. G. Hong, K. B. Park, S. W. Kim, J. J. Lee(KAIST, Korea)

B2-4 *An Optimization Method of a Combinatorial Optimization Problem using a Replicator Equation*
K. Tsuchiya(Kyoto University, Japan)
K. Tsujita, Y. Inoue(Osaka University, Japan)

B2-5 *Nonlinear Numerical Optimization with Use of a Hybrid Genetic Algorithm Incorporated the Modified Powell Method*
M. Okamoto, T. Nonaka, S. Ochiai, D. Tominaga
(Kyushu Institute of Technology, Japan)

B2-6 *A Parallel Genetic Algorithm for Matching and Similarity Measure of Graphs*
Y. Wang, N. Ishii(Nagoya Institute of Technology, Japan)

Session A3: Fuzzy and Neural Network

A3-1 *A Fuzzy Classifier System for Evolutionary Learning of Robot Behaviors*
Y. Iwakoshi(Chyubu Hitachi Electric Co., Ltd, Japan)
T. Furuhashi, Y. Uchikawa(Nagoya University, Japan)

A3-2 *A Fuzzy-Logic Approach to Industrial Control Problems*
D. J. G. James, K. J. Burnham(Coventry University, UK)

A3-3 *Computational Analysis of Acquired Dyslexia of Chinese Characters based on Neural Networks*
S. Tsumoto, H. Tanaka(Tokyo Medical and Dental University, Japan)

A3-4 *The Improved Radial Basis Function Neural Network and Its Application*
X. Wang, H. Shao(Shanghai Jiao Tong University, China)

A3-5 *A Temporal Radial Basis Function Neuro-Tracker*
C. G. Looney(University of Nevada, USA)

Session A4: Artificial Sensory Organ

A4-1 *Artificial Retina Chip*
K. Kyuma, J. Ohta(Mitsubishi Electric Corporation, Japan)

A4-2 *Vision Chip Architecture With Light Adaptation Mechanism*
H. Kobayashi(Yokogawa Electric Corp., Japan)
T. Matsumoto, K. Tanaka(Waseda University, Japan)
T. Yagi(Kyusyu Institute of Technology, Japan)

A4-3 *Artificial Passive Vision Using High Speed Pixel Matching*
H. Hanaizumi, T. Tsumashima(Hosei University, Japan)
F. Fujimura(University of Tokyo, Japan)

A4-4 *Artificial Active Vision Using Spatial Coding by m-sequence*
S. Fujimura, S. Kiyasu(University of Tokyo, Japan)

A4-5 *Building Ears for Robot : Sound Localization and Separation*
J. Huang, N. Ohnishi, N. Sugie(RIKEN, Japan)

A4-6 *Artificial Plant Trees Based on IFS*
X. Li(University of Aeronautics and Astronautics, China)
M. Sugisaka(Oita University, Japan)
Y. G. Zhang(Academia Sinica, China)

Session B3 : Mobil Robot and Vehicle

B3-1 *Dynamic Behavior Arbitration for Autonomous Mobile Robots Using Immune Networks-Evolution of Affinities among Antibodies-*
A. Ishiguro, T. Kondo, Y. Watanabe, Y. Uchikawa
(Nagoya University, Japan)

B3-2 *Auto Navigation on the wheel Chair*
H. Wang, C. Kang, T. Ishimatu(Nagasaki University, Japan)
T. Ochiai(Ube Technical College, Japan)

B3-3 *An Emergence of Fuzzy Control Rules for Mobile Robots using DNA Coding Method*
T. Yoshikawa, T. Furuhashi, Y. Uchikawa(Nagoya University, Japan)

B 3-4 *Experimental Study on Autonomous Mobile Robot Acquiring Optimal Action to Avoid Moving Obstacles*
T. Aoki(Nagoya Municipal Industrial Research Institute, Japan)
T. Oka, T. Suzuki, S. Okuma(Nagoya University, Japan)

B3-5 *The Development of A Practical Control Method for an Intelligent Mobile Vehicle*
M. Sugisaka, X. Wang(Oita University, Japan)
J. J. Lee(KAIST, Korea)

B3-6 *Development of A Stair Climbing Mobile Robot for Disabled and Elderly People*
T. Mabuchi, T. Yamada, K. Shiraki, K. Awa, T. Nagasawa
(Kansai University, Japan)

Session B4: Bio and Bio-Mimetic

B4-1 *Linear Systems Analysis of Amino Acids Production*
H . Hirayama, Y. Ishikawa, T. Nozawa, K. L. We, Y. Fukuyama
(Asahikawa Medical College, Japan)

B4-2 *Optimization of Growth of Peptide Chain by Ribosomes on a Messenger RNA*
H. Hirayama, Y. Fukuyama(Asahikawa Medical College, Japan)

B4-3 *Optimal Control in Active Transport in Biological Membrane*
H. Hirayama, Y. Fukuyama(Asahikawa Medical College, Japan)

B4-4 *Identification of a Transport System*
A. P. Wang(Arizona State University, USA)
S. Ueno(Kyoto School of Computer Science, Japan)

Session A5: Evolution

A5-1 *The Artificial Evolution Robot Control Systems*
P. Husbands(University of Sussex, UK)

A5-2 *Hardware Evolution -a real "life on the silicon"*
H. Hemmi, K. Shimohara
(ATR Human Information Processing Research Labs, Japan)

A5-3 *Adaptive Evolution of Holon Networks by an Autonomous Decentralized Method*
N. Honma, K.Abe(Tohoku University, Japan)
M. Sato(Tohoku Institute of Technology, Japan)
H.Takeda(Tohoku Gakuin University, Japan)

A5-4 *CAM-BRAIN The Evolutionary Engineering of a Billion Neuron Artificial Brain by 2001 which Grows/Evolves at Electronic Speeds inside a Cellular Automata Machine(CAM)*
H. D. Garis(ATR Human Information Processing Research Labs, Japan)

A5-5 *Evolution of Locally Defined Learning Rules and Their Coordination in Feedforward Neural Networks*
H. Murao, S. Kitamura(Kobe University, Japan)

A5-6 *Artificial Evolution and Real Robots*
I. Harvey(University of Sussex, UK)

Panel Discussion A6

Title: Coexistance between human being and robots

including artificial life

Chair: M. Sugisaka(Oita University, Japan)

J. Casti: Santa Fe Institute(Prof. Technical Univ. of Viena)
C. Langton: Santa Fe Institute
W. R. Wells: Univ. of Nevada-Las Vegas (Dean of Engineering)
J. M. Epstein: Santa Fe Institute (The Brookings Institution)
S. Rasumussen: Santa Fe Institute (Los Alamos National Laboratory)
F. Ota: Toshiba Corporation Oita Works(General Manager)
H. Miura: University of Tokyo
T. Yamakawa: Kyusyu Insutitute of Technology (Dean of Faculty of Information Engineering)
S. Ueno: Kyoto School of Computer Science Information Science Laboratory (Emeritus Professor of Kyoto University)

Session B5: Manipulation and Autonomous System

B5-1 *Fine Motion Strategy for Skill-Based Manipulation*
A. Nakamura, T. Ogasawara, H. Tsukune
(Electrotechnical Laboratory, Japan)
T. Suehiro(Real World Computing Partnership, Japan)

B5-2 *Artificial Realization of Human Skill for Robot Manipulator Control*
M. Nakamura, S. Goto(Saga University, Japan)
N. Kyura(Kinki University, Japan)

B5-3 *Spontaneous Behavior for Cooperation of Distributed Autonomous Robots*
T. Shibata(Mechanical Engineering Laboratory, AIST, MITI, Japan, Artificial Intelligence Laboratory, MIT, USA)
K. Ohkawa(Tsukuba University, Japan)
(Mechanical Engineering Laboratory, AIST, MITI, Japan)

B5-4 *Design Principles of Autonomous Agents: A Case Study of Classification*
R. Pfeifer(University of Zurich-Irchel, Switzerland)

B5-5 *Distributed and Autonomous Sensing based on Immune Network*
Y. Ishida(Nara Institute of Science and Technology, Japan)

B5-6 *Force/Position Control of Robot Manipulator via Motion Dynamics*
S. Jeong, K. Im, J. Kim, W.Ham(Chonbuk National University, Korea)

Session B6: Chaos and Robots

B6-1 *Associative Readout from a Chaos Network enjoying Chaotic Itinerancy*
T. Yamakawa(Kyusyu Institute of Technology, Japan)

B6-2 *Chaotic Local Search Algorithm*
C. Choi, J. J. Lee(KAIST, Korea)

B6-3 *Chaos Control on Multi-Branch U.L.N.*
M. Koga, K. Hirasawa, J. Murata, M. Ohbayashi
(Kyusyu University, Japan)

B6-4 *Autonomous Micro-Robot "Kity" for Maze Contest*
J. H. Kim, M. J. Chung, H. S. Shin, S. W. Lee(KAIST, Korea)

B6-5 *Deadlock Resolution Using Hand-to-Hand Motion in Group Robots*
H. Ishihara, T. Fukuda, F. Arai, N. Hiraoka
(Nagoya University, Japan)

Session C1: Self-Organization

C1-1 *Self-Assembly Method for Mechanical Structure*
S. Murata, H. Kurokawa, K. Tomita, S.Kokaji
(Mechanical Engineering Laboratory, AIST, MITI, Japan)

C1-2 *A Self Organizing Evolutionary Algorithm*
I. K. Jeong, J. J. Lee(KAIST, Korea)

C1-3 *A Self-Organization Learning Algorithm for Visuo-Motor Coordination in Unstructured Environments*
H. B. Zha, T. Onitsuka, T. Nagata(Kyusyu University, Japan)

C1-4 *Proposal of Decentralized Consensus-Making Mechanisms Based on Immune System*
A. Ishiguro, Y. Watanabe, Y. Uchikawa(Nagoya University, Japan)

C1-5 *Towords Designing Artificial Neural Networks by Evolution*
X. Yao, Y. Liu(University of South Wales, Australia)

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Author Index

Abe, K. A5-3
Aoki, T. B3-4
Arai, F. B6-5
Arimoto, S. B1-1
Arthur, B. PS-3
Awa, K. B3-6
Burnham, K. J. A3-2
Casti, J. .... OP
Choi, C. B6-2
Eom, T. D. A2-1
Epstein, J. PS-4
Fujimura, S. A4-3
Fujimura, S. A4-4
Fukuda, T. B6-5
Fukuyama, Y. B4-2
Fukuyama, Y. B4-1
Fukuyama, Y. B4-3
Furuhashi, T. B3-3
Furuhashi, T. A3-1
Garis, H. D. A5-4
Gomi, T. B1-2
Goto, S. B5-2
Hachino, T. B2-1
Ham, W. B5-6
Hanaizumi, H. A4-3
Harvey, I. A5-6
Hemmi, H. A5-2
Hiramatsu, H. A1-5
Hiraoka, N. B6-5
Hirasawa, K. B6-3
Hirasawa, K. B1-3
Hirayama, H. B4-3
Hirayama, H. B4-1
Hirayama, H. B4-2
Ho, K. H. L. A1-2
Hong, S. G. B2-3
Honma, N. A5-3
Huang, J. A4-5
Husbands, P. A5-1
Ichikawa, S. B1-6
Im, K. B5-6
Inoue, Y. B2-4
Ishida, Y. B5-5
Ishida, Y. A1-1
Ishiguro, A. C1-4
Ishiguro, A. B1-6
Ishiguro, A. B3-1
Ishii, M. B1-5
Ishii, N. B2-6
Ishikawa, H. B6-5
Ishikawa, Y. B4-1
Ishimatsu, T. B3-2
Iwakoshi, Y. A3-1
James, D. G. A3-2
Jeong, I. K. C1-2
Jeong, S. B5-6
Jinzenji, T. A1-4
Jung, M. J. B6-4
Kang, C. B3-2
Kashiwagi, H. A2-6
Kawata, Y. A2-5
Kim, J. B5-6
Kim, J. H. B6-4
Kim, S. W. B2-3
Kita, H. A2-3
Kitamura, S. A1-5
Kitamura, S. A5-5
Kiyasu, S. A4-4
Kobayashi, H. A4-2
Koga, M. B6-3
Kokaji, S. C1-1
Kondo, T. B3-1
Kuboshiki, S. B1-6
Kurematsu, Y. A1-5
Kurokawa, H. C1-1
Kyuma, K. A4-1
Kyura, N. B5-2
Langton, C. G. PS-1
Lee, J. J. A2-1
Lee, J. J. B6-2
Lee, J. J. C1-2
Lee, J. J. B2-3
Lee, J. J. B3-5
Lee, S. W. B6-4
Li, X. A4-6
Liu, Y. C1-5
Looney, C.G. A3-5
Mabuchi, T. B3-6
Matsumoto, T. A4-2

Miura, H. PS-2
Murao, H. A5-5
Murata, J. B6-3
Murata, J. B1-3
Murata, S. C1-1
Musya, T. PS-1
Nagasawa, T. B3-6
Nagata, T. C1-3
Nakamura, A. B5-1
Nakamura, M. B5-2
Nishikawa, Y. A2-3
Nonaka, T. B2-5
Nozawa, T. B4-1
Ochiai, S. B2-5
Ochiai, T. B3-2
Ogasawara, T. B5-1
Oguro, R. B2-1
Ohbayashi, M. B6-3
Ohbayashi, M. B1-3
Ohkawa, K. B5-3
Ohnishi, N. A4-5
Ohnishi, N. A1-2
Ohta, J. A4-1
Oka, T. B3-4
Okamoto, M. B2-5
Okuma, S. B3-4
Onat, A. A2-3
Onitsuka, T. C1-3
Park, K.B. B2-3
Pfeifer, R. B5-4
Rasmussen, S. PS-5
Ray, T. S. PS-2
Saita, H. B1-5
Sakata, M. A2-6
Sano, M. B1-4
Sasaki, M. A1-4
Sato, M. A5-3
Sawada, Y. B1-4
Shao, H. A3-4
Shibata, T. B5-3
Shim, H. S. B6-4
Shimohara, K. A5-2
Shiraki, K. B3-6
Suehiro, T. B5-1
Sugawara, K. B1-4
Sugie, N. A4-5
Sugisaka, M. A4-6
Sugisaka, M. B3-5
Sugisaka, M. A2-2
Sugisaka, M. A2-4
Suzuki, T. B3-4
Suzuki, Y. A1-3
Takata, H. B2-1
Takeda, H. A5-3
Tanaka, H. A3-3
Tanaka, H. A1-3
Tanaka, K. A4-2
Tanie, K. B5-3
Tominaga, D. B2-5
Tomita, K. C1-1
Tsuchiya, K. B2-4
Tsuji, T. B2-1
Tsujita, K. B2-4
Tsukune, H. B5-1
Tsumashima, T. A4-3
Tsumoto, S. A3-3
Tsumoto, S. A1-3
Uchikawa, Y. B3-3
Uchikawa, Y. A3-1
Uchikawa, Y. C1-4
Uchikawa, Y. B1-6
Uchikawa, Y. B3-1
Ueno, S. B4-4
Umeda, N. B2-1
Wang, A.P. B4-4
Wang, H. B3-2
Wang, X. A3-4
Wang, X. B3-5
Wang, Y. B2-6
Watanabe, Y. C1-4
Watanabe, Y. B3-1
We, K.L. B4-1
Yagi, T. A4-2
Yamada, T. B3-6
Yamakawa, T. B6-1
Yamamoto, H. B2-2
Yao, X. C1-5
Yashima, Y. A2-5
Yoshikawa, T. B3-3
Zha, H. B. C1-3
Zhang, Y. G. A4-6

Would-Be Worlds: Toward a Theory of Complex Systems

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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:

$$\rightarrow \text{observation} \rightarrow \text{theory} \rightarrow \text{hypothesis} \rightarrow \text{experiment} \rightarrow$$

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 neo-darwinian 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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Numerical Analysis of the State of Mind

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Abstract

The state of mind is supported by the brain activity, and hence features of the state of mind appear in the scalp potentials or EEGs (Electroencephalo-gram). Therefore, it is possible to estimate the state of mind by proper mathematical manipulations on spatio-temporal behavior of EEGs. The emotional state is decomposed into more elementary states. Currently ten electrodes are used and the four elementary states, *anger, sadness, joy, and relaxation,* are adopted. More electrodes would allow more elementary emotional states to be included in the analysis. The features are found in the cross-correlation coefficients of 45 pairs of EEG channels in the theta (5-8 Hz), the alpha (8-13 Hz), and the beta (13-20 Hz) bands. The totally 135 variables are obtained and they are linearly combined into four components which indicate levels of the four elementary emotional states. The maximum time resolution of the emotion analysis is 0.64 second and it is done in real time. This new technique has a wide variety in the medical and non-medical areas. This new technology suggests a possibility of direct control of systems by the human emotional state.

1. Introduction

The scalp potential (electro-encephalogram, EEG) is generated by electric activities of neurons in the brain. It is rich in information about the state of the brain, or in other words about the state of mind. Features of the state of mind, however, are buried in the spontaneous EEG generated by the other brain activities, and sophisticated mathematical manipulations will be required to pick up the required features from the unwanted ones. Such *event-related* potentials are obtained by synchronous averaging of EEG by repeating the same events. However, synchronous averaging is not possible in estimating the state of mind or the emotional state because always we have to analyze single events. The feature extraction of the emotional state need to be done through single events..

We have solved this problem as described in Sec. 2. The emotional state is decomposed into four elementary states as *anger, sadness, joy,* and *mental relaxation.* This technique is similar to spectral analysis and we have given to it the name of *Emotion Spectrum Analysis,* or *ESA* in abbreviation. The present method expresses the state of the human emotion numerically, which would allow manipulation of a non-human machine according to the state of mind.

2. Method of Analysis

Ten disk electrodes are placed on the scalp at positions F_{P1}, F_{P2}, F_3, F_4, T_3, T_4, P_3, P_4, O_1, and O_2 according to the International 10-20 Standard, and scalp potentials are recorded with a reference electrode on the right ear-lobe. The electric potentials are sampled at 100 Hz, and then separated in the theta, alpha and beta frequency bands by means of FFT. Values of the cross-correlation coefficients on 45 (= ${}_{10}C_2$) channel pairs are evaluated in every

5.12 seconds (it is possible to shorten this time down to 0.64 second); totally, 135 such variables are obtained. The set of these 135 variables is the input vector y; this is linearly transformed to a 4-vector $z = (z_1, z_2, z_3, z_4)$ by operating a transformation matrix **C** on y. Magnitudes of these components indicate levels of these elementary emotional states. We call **C** the ***emotion matrix***, and z the ***emotion vector***; they are related as

$$\mathbf{C}.\mathbf{y} + \mathbf{d} = \mathbf{z} \qquad (1)$$

where d is a constant vector.

Numerical values of the emotion matrix elements were obtained in the following way. Seven people who have been well trained in imaging participated in preparing the emotion matrix. They first imaged *anger*, and 5.12-sec EEG segments were cut out from their ten-channel EEGs; this process was repeated for all the other elementary emotional states. The numerical values of the matrix elements were determined in such a way that z = (1, 0, 0, 0), (0, 1, 0, 0), (0, 0, 1, 0) and (0, 0, 0, 1) for the four emotional states, respectively, and (0, 0, 0, 0) for the control state in which no special emotion was activated; numerical solutions are obtained in either under-determined or over-determined condition. These elementary emotional states are approximately orthogonal, or in other words they are almost independently generated. Each vector component is an index of the related emotional level.

If the emotion matrix is prepared for a particular person, its applicability is limited to this particular person only, losing general applicability because the matrix includes features of the emotional states as well as personal characters. Therefore, personal characters must be smeared out by preparing the emotional matrix based many subjects.

3. Noise Reduction

The emotion vector should have positive components only according to the definition. In the real situations, however, it shows negative as well as positive value. There are many other emotional states which the four elementary ones cannot cover. The emotion matrix cannot suppress their appearance in the 4-dimensional emotion space; their appearance in the 4-dimensional ***emotion space*** will be random, making *noise*. The noise level is estimated as standard deviation σ of the negative contribution in each vector component.

The factor $f(z)$ is multiplied to the derived emotion vector components, which is

$$f(z) = tanh\left(\frac{z}{4\sigma}\right) = \frac{exp\left(\frac{z}{4\sigma}\right) - exp\left(-\frac{z}{4\sigma}\right)}{exp\left(\frac{z}{4\sigma}\right) + exp\left(-\frac{z}{4\sigma}\right)} \qquad (2)$$

for $z > 0$ and $f(z) = 0$ for $z < 0$. The smaller part of the emotion index that is comparable to the noise level is suppressed by this factor. On the other hand, however, the index value itself is influenced by the noise. This effect is removed by smearing the index values by the moving average. The smoothed index $\bar{z}_n$ at the nth time point is calculated as

$$\bar{z}_n = 0.1(z_{n-2}+z_{n+2})+0.2((z_{n-2}+z_{n+2})+0.4z_n \qquad (3)$$

When a subject has *anger* in mind, the index of *anger* acquires a high level. However, the index of *anger* does not always mean that the subject has *anger* in mind but that the subject has mental stress in general. In the same way the index of sadness means that the subject is in a depressed state. To avoid misunderstanding, the indexes for *anger, sadness, joy* and *relaxation* are named as *N1*, *N2*, *P1* and *R*.

4. Emotional State and EEG cross-correlation

Each emotion matrix element is concerned with a pair of EEG channels in one of the three frequency bands. A larger matrix element in magnitude (regardless of plus or minus) plays a more important role in extracting features of the emotional components. Fig.1 shows magnitudes of emotion matrix elements in reference to respective EEG channels indicated by crosses. Open and dark circles refer to positive and negative cross-correlation coefficient, respectively, and the radius represents the magnitude of the coefficient in four steps.

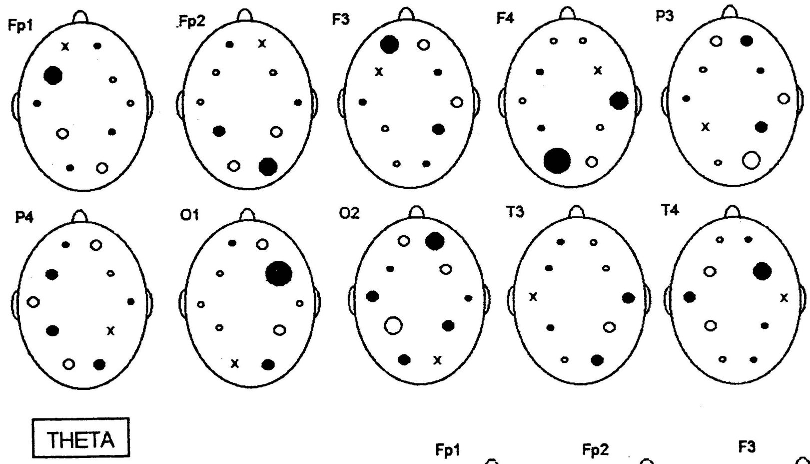
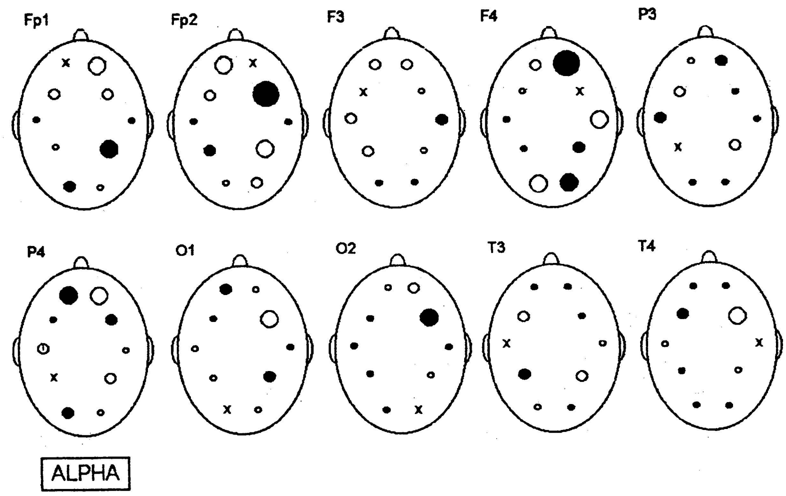


Fig. 1—1

Fig. 1—2



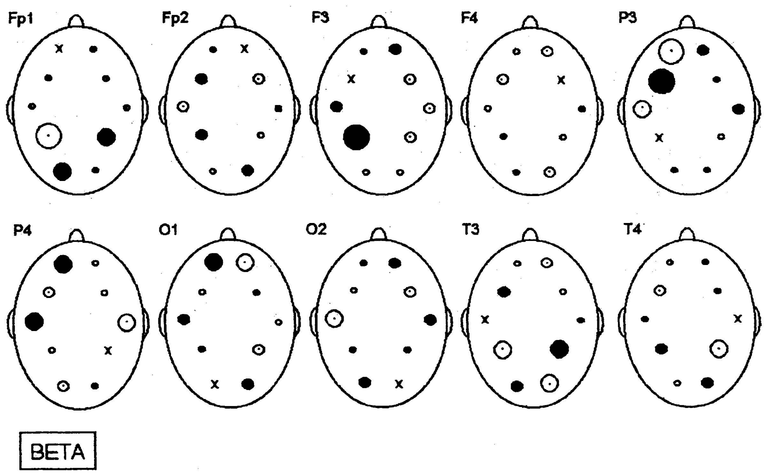


Fig. 1—3

5. Results of Emotion Analysis

A female subject did algebraic tasks for an hour. After quitting this work the emotion analysis started and the result is shown in Fig. 2. This figure shows magnitudes of the four indexes, *N1*, *N2*, *P1* and *R*, from the top, and each bar corresponds to 5.12 sec. Initially the subject showed signals mainly in *N1* and *N2*. *N1* indicates mental stress or excitation; when the subject is psychologically tired this index is usually accompanied by *N2*. When, on the other hand, the subject is excited with interest in something, *N1* is accompanied by *P1*. In the present case, the subject was tired in mathematical work. Then she began to listen to her favorite music; immediately these two indexes decreased to low levels, and at the same time index *P1* (characterizing joy) increased which, however, was reduced after two or three minutes probably because of habituation. Interesting to say, indexes *N1* and *P1* were fluctuating in the opposite phase. After the music was over, the same state continued.

The second example is shown in Fig. 3. Two male subjects A and B were doing algebraic tasks. Subject B finished the work earlier than subject A and told the examiner that he had finished it. Subject showed relatively high relaxation index *R* and low stress index *N1* before subject B finished his work. When he found that he was behind his partner in finishing the work, his relaxation level lowered and the stress index increased.

6. Conclusion

Our technique of making numerical evaluation of the state of mind at high time resolution is new, and it will contribute to artificial intelligence, robotics, and so on.

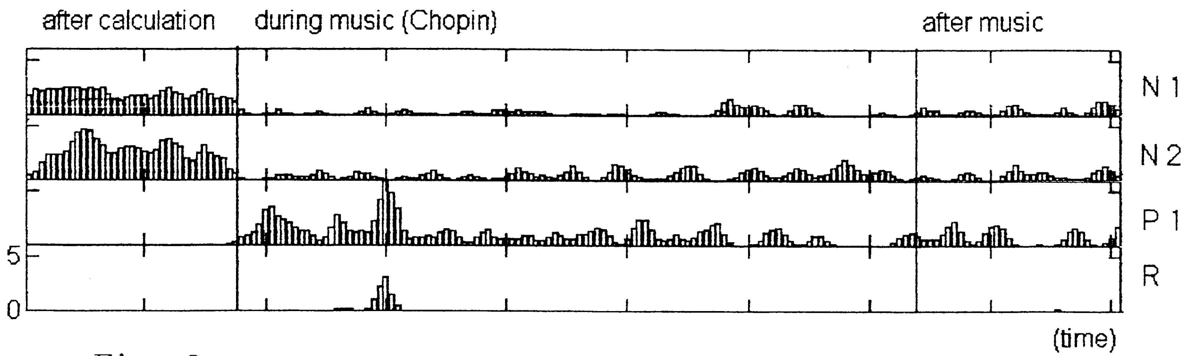


Fig. 2

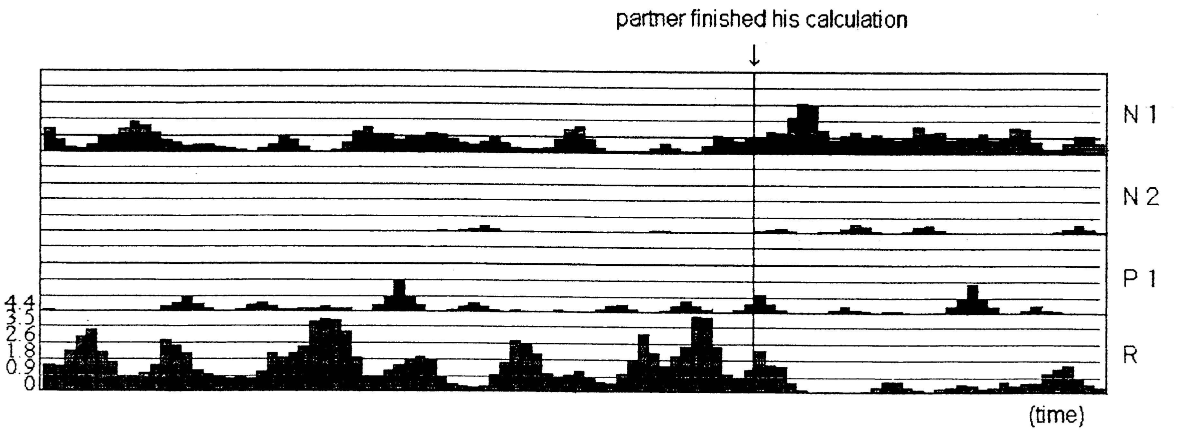


Fig. 3

Evolving Complexity

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Abstract

Humans have been practicing applied evolution since the dawn of agriculture, long before the development of the theory of evolution. The domestication and breeding of plants and animals is based on the application of artificial selection to captive populations. However, our management of evolution has taken place at the "micro" level, the alteration of existing species. We have never been able to harness and manage the more creative properties of evolution: the origin of new species, and the emergence of complexity itself. We are able to guide the evolution of poor quality wild corn into high quality domestic corn, however, we can not guide the evolution of algae into corn. To manage complexity increase in synthetic evolutions requires an entirely new approach: the creation of "natural" ecological communities where complexity increase can occur through evolution by natural selection.

1 Synthetic Evolution

It has been said that "life is art". If life is art, evolution is the artist. The creative products of evolution include the human body and mind, the cheetah running down its prey, the mahogany tree, the humming bird pollinating a flower. These living works of art exceed in beauty, and depth of structure and process, anything produced by the best of human artists. In fact, human artists themselves are products of evolution.

Human artists express themselves in many media: oil paint, clay, stone, music, cinema. What is the medium of expression of evolution? On Earth, evolution is best known for its works in the medium of carbon chemistry. However, it has recently been demonstrated that evolution can work in other media. In the last few decades, evolution has begun to express its creative potential through the digital medium.

Much of the work with evolution in the digital medium has had clear engineering objectives, but some work has simply been an exploration of the process of evolution in an unfamiliar medium. In this latter case, the conditions are created for evolution by natural selection to take place among self-replicating computer programs. The result is a diversifying phylogeny of "digital organisms", in a "natural" ecological community within cyberspace.

To the extent that an ecological community of freely evolving self-replicators can be considered alive, this represents another instance of life, but a very alien life. If we could travel to other planets and observe life there, it would probably be organic life, and to that extent, somewhat familiar. But life embedded in the radically different medium of digital computation would be even more alien than extra-terrestrial life.

Freely evolving digital organisms are an instance of evolution, not a model or simulation of organic evolution. Like a chemostat full of evolving bacteria and viruses, a computer full of evolving digital organisms could be thought of as a model system for the experimental study of evolution. However, the evolving digital organisms are no more a simulation of evolution that are the evolving bacteria and viruses.

2 Complexity Increase

Earth's most creative evolutionary transitions were reviewed recently [3]. They seem to occur relatively abruptly, compared to the background rate of evolutionary change. Some of the major transitions noted were: origin of chromosomes, origin of eukaryotes, origin of sex, origin of multi-cellular organisms, origin of social groups.

Of these major transitions, perhaps the most dramatic, and best known, was the rapid origin and diversification of large multi-cellular organisms from micro-scopic single celled ancestors, in what has come to be known as the Cambrian explosion of diversity [1]. It has understandably been called evolution's "big bang", when there was a dramatic inflation of complexity of organisms, and species diversified rapidly into an ecological void.

Because the Cambrian explosion generated the largest of organic life's complexity increases, it is interesting to consider what its digital analogue may be. At its most fundamental level, the Cambrian explosion arose out of the transition from single to multi-cellular organisms. The digital analog would be a transition from serial to parallel processes.

If we make an analogy between the cell and the processor, then modern multi-cellular organisms are parallel programs on a scale of complexity that vastly exceeds any existing computer software. In organic life, the program is the genome, based on nucleic acid sequences. In humans this program has roughly three billion bases. However, no individual cell expresses all the genes in the genome. Each cell expresses a small subset of the genes, and this subset defines which "cell type" the cell is. It may be a skin cell, liver cell, brain cell, etc. depending on what subset of genes it expresses.

The human body is thought to have several hundred distinct cell types, with a total of trillions of cells. This corresponds to the two main types of parallelism in computer software: SIMD and MIMD. In SIMD parallelism there is a single instruction pointer shared by all of the processors, so every CPU executes the same code in absolute synchrony. In MIMD parallelism, each CPU has its own instruction pointer, so each processor is capable of executing a different set of code.

SIMD parallelism corresponds roughly to multiple cells of a single cell type, in that in both cases, the same genetic code is being expressed. MIMD parallelism corresponds to multiple cells of different cell types in that different cells are expressing different code. Large modern multi-cellular organisms combine both SIMD and MIMD parallelism on a massive scale. However, most parallel computer software is primarily of the SIMD type. The reason is that SIMD software is approximately the same as serial software, but executed simultaneously on many processors and presumably operating on different data. However, existing MIMD software is much simpler that the genomes of organic multi-celled organisms. Such software is just too complex to write. While existing MIMD computer hardware has the capability of having hundreds or thousands of processors each executing different code, while all cooperating on a single task, there does not exist a human art for writing such software. It is beyond the capability of programmers to write code involving more than a few distinct processes.

3 Tierra

My own work with digital evolution is an attempt to generate a free process of evolution by natural selection. I have set up a system of self-replicating computer programs, where the only clearly defined "fitness" criteria imposed on the system is the same as what is found in organic evolution: the ability to replicate, or transmit genetic material to future generations. My system, called Tierra (Spanish for Earth) creates the basic Darwinian scenario: self-replicating entities in a finite environment with heritable genetic variation, inside the computer.

In Tierra, the self-replicating entities are executable machine code programs, which do nothing more than make copies of themselves in the RAM memory of the computer. Thus the machine code becomes an analogue of the nucleic acid based genetic code of organic life. The machine code programs occupy space in the RAM memory, thus the memory provides an analogue of the physical space of organic life. Each program "owns" the block of memory that it occupies, and has an exclusive privilege of writing on its own memory blocks. However, any process may read, or execute the machine instructions in any part of memory. Thus the partial (only write) privilege surrounding the space occupied by the program is thought of as analogous to a semi-permeable membrane surrounding organic cells, partially protecting the internal chemistry from disruption from the surroundings.

Genetic variation is introduced into the population of replicating programs by randomly flipping bits in the machine code. This is analogous to mutations involving substitutions of nucleic acids in the DNA sequence of organic life. Additional noise is introduced into the system in the form of occasional errors in the computations performed by the CPU (central processing unit).

The replication of the programs is brought about through their execution by the CPU of the computer. Thus CPU time provides the analogue of the energy that drives the metabolism of organic life.

The results of the evolutions that have been observed so far represent a variety of solutions to the problem of self-replication of machine code programs. We might consider these solutions to fall into two broad classes: "ecological solutions", and "optimizations". Ecological solutions involve interactions between the programs sharing the memory, whereas optimizations involve innovations within the individual algorithms that result in faster replication.

We know that evolution embedded in the medium of carbon chemistry is capable of generating parallel software combining both SIMD and MIMD parallelism on an astronomical scale. However, we don't know the capabilities of evolution when embedded in the medium of digital computation. The experiments that have been conducted so far show a surprising ability of evolution to reorganize and improve machine code.

However, organic evolution was able to increase the complexity of the replicators by many orders of magnitude. So far digital evolution has shown small increases of complexity, perhaps by a factor of as much as two or three. Is digital evolution capable of very large spontaneous complexity increases, and if so, under what conditions? The answers to these questions can only be determined by experimentation.

An effort is underway to create conditions that might provoke evolution to generate substantially greater complexity in digital replicators. I am preparing what I call the "biodiversity reserve for digital organisms." This will be based on a networked version of the Tierra software. We will attempt to get thousands of people to run network Tierra on their computers, and all of these computers will be connected into a virtual sub-net of the internet, within which digital organisms will be able to move freely from computer to computer.

This configuration offers two advantages over the original single-computer version of Tierra: greater size, and greater complexity of temporal and spatial patterns of resources.

There will be a dramatic increase in the size of the space, and the amount of CPU cycles available to the digital organisms. The single-machine version is generally run with a memory space of one or two hundred thousand bytes. However, a single complex digital organism could exceed that size.

It is believed that evolution can only generate great complexity in the context of an evolving ecological community, as biotic evolutionary interactions are an important driving force in evolution. Thus we need a space that can hold entire populations of many species of large organisms. Suppose that we want to support, minimally, a hundred species, each with populations of five hundred individuals, with individuals of ten thousand bytes in size. This would require a space of about five hundred megabytes. While this space could be achieved on a single computer, there would be a very bad ratio of memory to CPU power. Distributing the memory over many computers provides a better memory/CPU ratio.

While greater size is an absolute requirement, large size alone would probably not provoke evolution towards greater complexity. However, the distributed model provides a great complexity of temporal and spatial patterns of resources. It is felt that this complexity could provide selective pressures for evolution to create complex adaptations to those patterns.

The network Tierra software will be run as a low-priority background process, like a screen saver. This means that when the user is actively using the computer, the Tierra software will sleep, receiving no CPU cycles, the energy source for the digital organisms. Any digital organisms who are present on the machine at that time will be frozen, unable to metabolize or reproduce.

This should create a strong selective pressure for individuals to move about the net, avoiding sleeping Tierra programs, and seeking those with a rich supply of CPU cycles. Evolution may generate behaviors that respond to temporal patterns in the availability of CPU cycles. For example, there is likely to be a daily cycle, with generally more free cycles at night when people are sleeping. So some digital organisms might evolve the behavior of migrating around the planet on a daily basis staying on the dark side of the planet.

The approach for managing the evolution of complexity that is being advocated here is to generate a "natural" ecological community of freely evolving digital organisms. The environment in which they live should include sufficient complexities to provide some selective pressures for increasingly complex behaviors to evolve. Once a significant impulse in the direction of complexity has occurred, the hope is that selective forces arising from interactions among the digital organisms can lead to an auto-catalytic increase in complexity.

It appears that this is what happened in organic evolution. In the Amazon region, there are rain forests on white sand soils, where the physical environment consists of clean white sand, air, falling water and sunshine. Embedded in this physical environment is the most complex ecosystem on earth, the tropical rain forest. In this ecosystem there are hundreds of thousands of species. These do not represent hundreds of thousands of adaptations to the physical environment, but rather, most of the adaptations of these species are with respect to the other living organisms that they interact with.

Life transforms the environment, such that the living component of the environment comes to predominate over the physical environment, after which most evolution involves adaptations to other living organisms. Thus the complexity of the living component of the environment comes to greatly exceed the complexity of the physical environment that it is embedded in.

The first evolution observed in Tierra was the origin of ecological interactions, which were based on adaptation to the presence of other digital organisms in the environment [2]. Thus this dynamic has been present in Tierra from the beginning. It is hoped that with the help of some impulse towards greater complexity, this dynamic can lead to a large spiraling upwards in complexity.

4 Practical Applications

How might we work with digital evolution to produce useful products? Although we have a well established practice of plant and animal breeding, our relationship to digital evolution is quite different. Our ancestors were able to go out into nature and observe many highly evolved and complex organisms. They found uses for some of these, such as the ancestors of, rice, corn, wheat, chickens, pigs, dogs, etc. They then bred them to produce the much improved domesticated plants and animals that we know today.

However, in the case of digital evolution, we are starting with very simple organisms that have not yet achieved the complexity to be useful, so our first objective is to evolve complexity. We have no prior experience with managing the evolution of complexity.

Probably any attempt to guide the evolution of algae to become corn, through artificial selection in the context of a breeding program, would prevent such a transition from occurring. I believe that we will never be able to guide the evolution of complexity by the use of artificial selection. To facilitate complexity increase we need a new and different approach.

I suggest that the most likely way to achieve complexity increase in digital evolution is through evolution by natural selection in an ecological community. No attempt should be made to provide fitness functions, or artificial selection, to guide evolution towards useful products. Rather, evolution should be free explore the possibilities without the burden of human "guidance".

Traditionally we have managed evolution through manipulating selective forces. In this new approach, our role is to create the conditions for complexity increase, rather than trying to guide it through artificial selection. This is an interesting scientific challenge, as the conditions that generate complexity increase are unknown. However, the process of attempting to generate a complexity increase, amounts to an experimental approach to the problem. We can try many different approaches, and if we are successful, we will be able to experiment with the system until we can find the minimal conditions that generate the behavior.

If a digital analog to the Cambrian explosion can be achieved, then it should be possible to establish the same kind of relationship to digital evolution that we have with organic evolution. We can go out into digital nature, and observe the complex products of evolution. While most digital organisms will have no application, it is likely that some will. We can observe them for interesting and potentially useful information processes. When we identify potentially useful digital organisms, we can capture them and subject them to selective breeding to enhance their performance on the application, and inhibit unruly wild behavior. Eventually the product can be neutered and sold to the end user.

We have seen the tremendous creative potential of evolution when expressed through the medium of organic chemistry. We do not yet know the full potential of evolution in the medium of digital computation. However, the initial experiments have been very promising, suggesting that it is worthwhile to make the effort to push digital evolution to its limits. If digital evolution has even a small fraction of the potential of organic evolution, it could result in information process of a complexity far beyond anything that we have experience with today. While there are many potential obstacles and technical problems along the way, the possible rewards for success make the risk worth taking. Yet it is a venture into the unknown for which we can not estimate the likelihood of success.

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INSECT-MODEL BASED MICROROBOT

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Abstract

It should be understood that the robot is not a simple automatic machine, but instead has certain level of intelligence. Many kinds of intelligent robots have been developed in the author's laboratory during the past 15 years. These robots perform many kinds of games like the cup & ball game, top-spinning, walking on stilts, etc. These robots apparently look intelligent, but are they really and truly intelligent? There is one opinion that these robots are no more than simple automatic machines which are controlled by a computer with sophisticated programs. If so, then what is actual robot intelligence? The author is trying to construct a new robotics --- insect-model based microrobotics --- in order to get a new concept of robot intelligence.

1 WHAT IS ROBOT INTELLIGENCE?

Intelligence for the robots shown in Fig. 1 is discussed below.

(1) INTELLIGENCE FOR FAST AND ACCURATE MOTION (Cup & ball game robot)

When the motion is slow, PTP(point to point) control works well. But for the fast motion, PTP control yields position error because for fast motion, the inertial forces (centrifugal force, Colioris force, etc. which act on the joint motors) are considerably large and feedback control is disturbed by them.

So-called " inverse dynamics " is a very effective control scheme for fast motion. The cup & ball game cannot be implemented by the usual industrial robot employing PTP control scheme. On the other hand, by employing the inverse dynamics, the robot played cup & ball game with a 95% success ratio. Inverse dynamics can be robot intelligence for fast and accurate motion.

(2) INTELLIGENCE FOR LEARNING (Inverted pendulum)

The ability to learn is one of the most challenging subject in robotics. The inverted pendulum robot was developed as an example of a robot which has learning ability. If the geometrical dimensions (length, weight, position of center of gravity, moment of inertia, etc.) are not given, learning control must be employed. During the first several minutes of the experiment, a person's hands help the pendulum to maintain the vertical attitude, but after several minutes the pendulum has learned to keep the vertical attitude all by itself.

(3) INTELLIGENCE FOR DYNAMIC BALANCE (The biped and the quadruped)

In the author's laboratory many kinds of bipeds have been developed. The biped (stilt type) is statically unstable but can be balanced dynamically. It has intelligence for dynamic balance[1]. Another type of biped (human type) has knee joints and ankle joints like a human. Eight motors are mounted in this robot in total, and it can walk more slowly than the stilt type. It also walks dynamically.

The quadruped also walks dynamically. Real animals support their bodies with two legs (not three legs) and swing the other two legs in the air even during a slow walk. At low speed, one fore leg and one hind leg on the same side are in the air together. This gait is called "pace". When the walking speed of an animal gets faster, the gait changes to "trot (diagonal two legs are in the air together)". The gait is selected by a minimum energy consumption criterion[2],[3].

(4) INTELLIGENCE FOR LEARNING THE ROPE (top-spinning robot)

The author can spin a top. However, it is very hard to teach another person how to spin a top. This means that writing a program for the top-spinning robot is also very hard. How fast should the arm move? At which position should the top be thrown forward? How strongly should the string be pulled back? The author learned these tricks by watching his father's play. For the robot, the trajectory of a human arm and a top during human top-spinning play was input into the computer through two video cameras (one camera in front, and one over the head) and the computer generated a program to reproduce the same motion of the arm and the top from human play. With this program the robot spins a top very skillfully. This example may be called " teaching by showing."

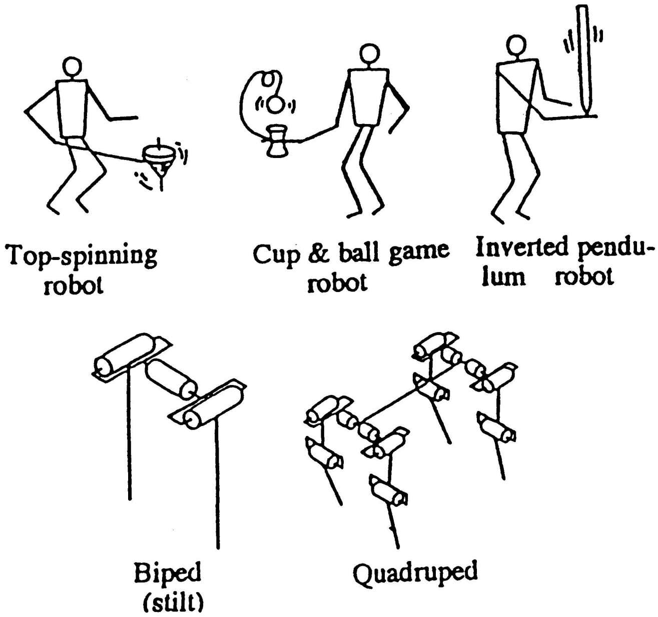

Fig. 1 Some Examples of Intelligent Robots which have been developed at the author's lab.

2 CAN A MACHINE HAVE ITS OWN WILL?

Several examples of robot intelligence were presented above. These robots complete dexterous tasks like a human does. However, the author is not sure whether these robots are as intelligent as a human, because all algorithms expressed in the program are developed by a human investigating the result of analysis of human play. The robot itself is not intelligent and it only follows the program given to it by a human. The robot has no will to play these games better and better.

On the other hand, the author practiced hard on cup & ball game, top-spinning, etc., so that he could play better than his friends during childhood.

Can a machine have will? This is a big question in robotics and AI technology. The author is trying to find a new way for a small but steady step to answer this question[4].

3 INSECT-MODEL BASED ROBOTICS (Microrobot)

An insect looks much more intelligent and more lively than robots introduced above. The insect looks to have a will. If an insect robot could be developed, it is possible to make it look truly intelligent. The author's laboratory started developing insect-model based robots about five years ago when looking for a new and different way to approach intelligent robots. Since the late 1980s, microtechnology has been highlighted as a promising technology for the development of very small sized mechanical systems. Fabrication of micromechanisms on a silicon wafer using IC process may be the key technology for developing mm sized microrobots.

Millimeter sized insects are all around us. The author considered that microtechnology should be applied to developing an insect-model based robot. Although there are still many problems which must solved to build real insect-model based microrobots, there are basic lines of solution for some problems with experimental results. This paper argues that insects will be good models for microrobots for design, control, actuation, etc., just as human beings or mammals are good models for normal-sized robots. In addition, an insect has only 10^5 neurons. The motion of an insect is produced by simple mechanisms such as "a reflex act". But it is interesting to the author that this motion looks intelligent. This is why the author is trying to develop an insect-model based robot.

4 EXTERNAL SKELETON

For developing microrobots, new design concepts must be constructed. For instance, a frictionless structure must be designed. Rotating joints must be avoided because at all rotating joint, there exists friction. Frictional forces are proportional to the sliding surface area size(L^2). Weight and inertial forces, however, are proportional to volume(L^3). As the size gets smaller, the frictional force exceeds the other forces and governs the motion of system. In an extreme case, motion cannot be realized when the system is subjected to normal actuation forces.

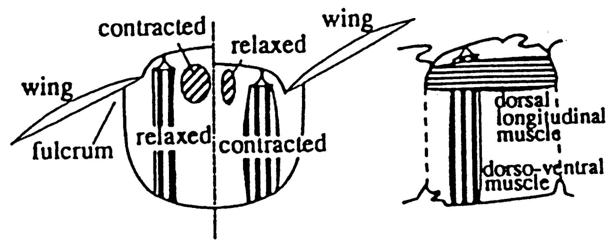

Fig.2 Cross section of an insect thorax. Distortion of the thorax causes beating of wings

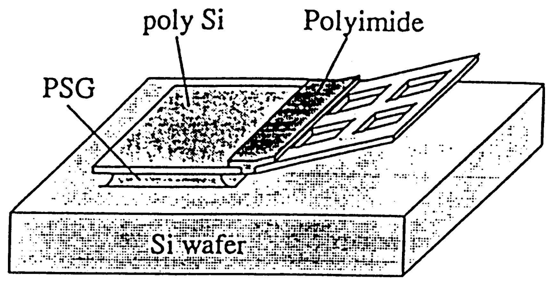

Fig. 3 Basic model of the external skeleton. Three dimensional structure is constructed by bending along the polyimide hinges.

We argue that knowledge about insects may be useful for developing microrobots. The insect has many interesting features, such as an external skeleton, elastic hinges (joints) , contracting-relaxing muscles, etc. These characteristics suggest basic design principles for microrobots.

The external skeleton of an insect consists of elastic(hard) cuticles connected by elastic (soft) hinges. In general, the elasticity of the cuticles is higher than the elasticity of the hinges.The motion of body parts like wings is based on the deformation of these elastic structures. Sliding friction does not exist there.

The cross-section of an insect (fly) thorax is shown in Fig. 2[5], illustrating the beating mechanism of the wing. The muscles are inside the skeleton, while muscles are outside the skeleton in humans.The downward movement of the wing is produced by distortion of the thorax caused by contraction of the dorsal longitudinal muscle. The upward movement results from distortion of the thorax produced by the dorso-ventral muscle.

Elasticity of the thorax plays an important role in the friction-free, high-speed wing movement. For most insects, the beating frequency coincides with the structural natural frequency of the thorax. Mechanical resonance is a good way to get large deformation with small external forces. This may be applicable for actuation in microrobots.

5 ORIGAMI STRUCTURE

Since the silicon IC process is planar, a three dimensional structure is difficult to make. The author's group is proposing a folding process like paper folding (ORIGAMI in Japanese) to make a 3D microstructure. To build an external skeleton, the author's group uses polysilicon as the rigid plate, and polyimide as the elastic joint. The basic structure of an external skeleton model is shown in Fig. 3. Polyimide is a thermosetting resin, and a hinge can be set at any angle by heating after bending it to the desirable angle. This structure can be fabricated easily by IC processes.

First, the development surface figure is made on a silicon wafer, and the folding lines are made of polyimide as shown in Fig. 3. The folding operation is done by a human with a microprobe under a microscope.

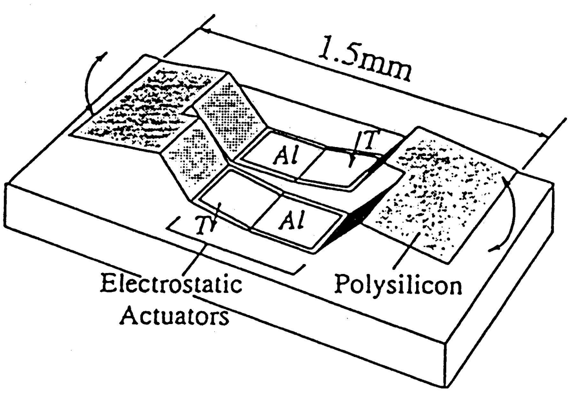

Fig. 4 Schematic figure of beating mechanism

6 MICROFLIGHT MECHANISM

The authors have developed the beating micromechanism actuated by electrostatic forces shown in Fig. 4. If an electric voltage is applied between Al plates and the base (silicon wafer), the plates move towards the base and the polysilicon wings bend up. When the frequency of the alternating voltage coincides with the natural frequency of mechanical vibration for the system, the beating amplitudes resonate. Including this example, several kinds of microflight mechanism have been developed. Magnetic force is also applicable for actuation of beating or microflight mechanisms, and a flying microrobot is now under development[6][7]. Fig. 5 shows a micro-flight mechanism[8]. It consists of three layers: polyimide, nickel, and polyimide. Nickel is sandwiched by two polyimide layers so as not to be attacked by HF while etching takes place to remove a sacrificial layer under polyimide. Both polyimide layers are spin-coated to 1 μm in thickness, and nickel is sputtered to 0.1 μm in thickness.

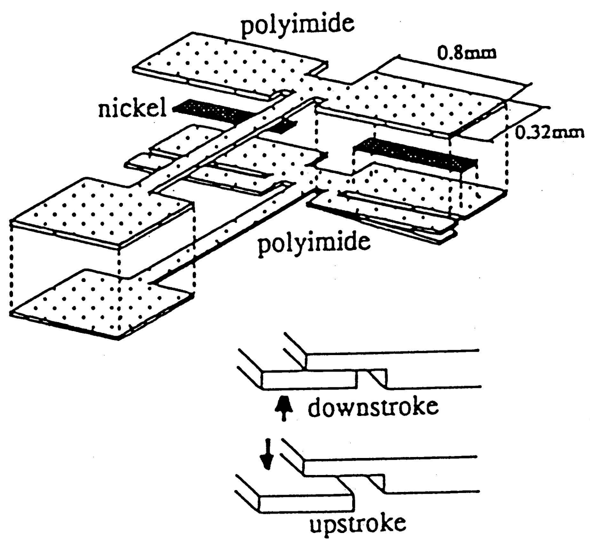

Fig. 5 Structure and dimensions of microflight mechanism

7 MICROANT-ROBOTS

In the author's laboratory a microant-robot has been developed, as shown in Fig. 6 and 7[9]. The gait for this robot is not the same as the real ant. The two middle legs kick the ground to move forward, while the other four legs touch the ground at all times to support the body. The ground vibrated with a very small amplitude(less than 1μm) and this vibration is transmitted to the middle leg through the ground. If the frequency of the vibration coincides with the natural frequency of the leg, it resonates with a large amplitude, providing the driving force by kicking the ground. The natural frequency of a leg is set by the length of the polyimide spring, so the two middle legs can have different natural frequencies.

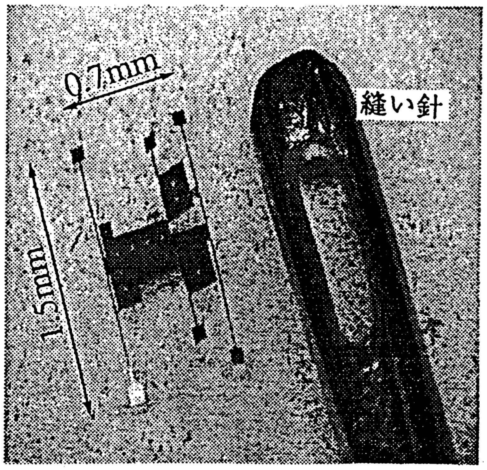

Fig. 6 Photograph of the fabricated microrobot alongside a sewing needle.

The robot can go straight, and turn to the right or to the left.

8 HYBRID INSECT ROBOT

A male silk moth pursues a female by following a pheromone. This action can be caused by only a few molecules of pheromone which arrive at the antenna of a male silk moth. A biological sensor was constructed as shown in Fig. 7. Two sensors were attached to a simple wheeled mobile robot to determined the direction of a pheromone trace. The robot followed the pheromone trace like a real male silk moth.

9 CONCLUSIONS

Several intelligent robots which have been developed in the author's laboratory have been introduced, but the author is not sure that these robots are truly intelligent because all control schemes have been constructed by humans and all computer programs have been written by humans. It can be said that they are no more than simple automatic machines which are controlled by a computer. The author is constructing a new technology -- - the insect-model based microrobot --- to look for something new in robot intelligence.

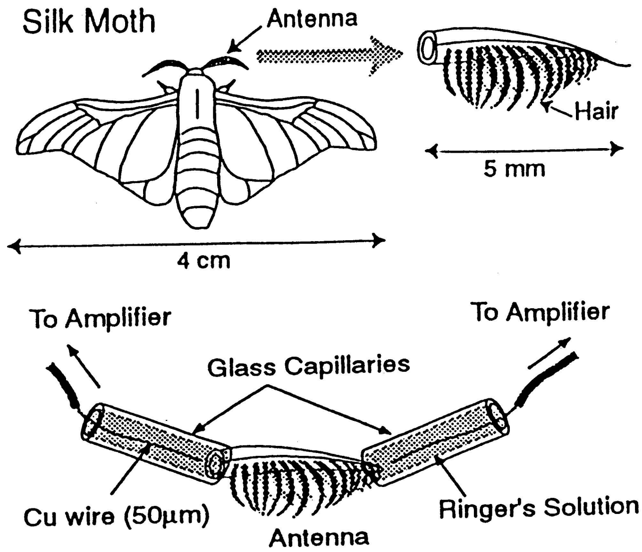

Fig. 7 Pheromone sensor

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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.

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Author Index

Abe, K. A5-3
Aoki, T. B3-4
Arai, F. B6-5
Arimoto, S. B1-1
Arthur, B. PS-3
Awa, K. B3-6
Burnham, K. J. A3-2
Casti, J. .... OP
Choi, C. B6-2
Eom, T. D. A2-1
Epstein, J. PS-4
Fujimura, S. A4-3
Fujimura, S. A4-4
Fukuda, T. B6-5
Fukuyama, Y. B4-2
Fukuyama, Y. B4-1
Fukuyama, Y. B4-3
Furuhashi, T. B3-3
Furuhashi, T. A3-1
Garis, H. D. A5-4
Gomi, T. B1-2
Goto, S. B5-2
Hachino, T. B2-1
Ham, W. B5-6
Hanaizumi, H. A4-3
Harvey, I. A5-6
Hemmi, H. A5-2
Hiramatsu, H. A1-5
Hiraoka, N. B6-5
Hirasawa, K. B6-3
Hirasawa, K. B1-3
Hirayama, H. B4-3
Hirayama, H. B4-1
Hirayama, H. B4-2
Ho, K. H. L. A1-2
Hong, S. G. B2-3
Honma, N. A5-3
Huang, J. A4-5
Husbands, P. A5-1
Ichikawa, S. B1-6
Im, K. B5-6
Inoue, Y. B2-4
Ishida, Y. B5-5
Ishida, Y. A1-1
Ishiguro, A. C1-4
Ishiguro, A. B1-6
Ishiguro, A. B3-1
Ishii, M. B1-5
Ishii, N. B2-6
Ishikawa, H. B6-5
Ishikawa, Y. B4-1
Ishimatsu, T. B3-2
Iwakoshi, Y. A3-1
James, D. G. A3-2
Jeong, I. K. C1-2
Jeong, S. B5-6
Jinzenji, T. A1-4
Jung, M. J. B6-4
Kang, C. B3-2
Kashiwagi, H. A2-6
Kawata, Y. A2-5
Kim, J. B5-6
Kim, J. H. B6-4
Kim, S. W. B2-3
Kita, H. A2-3
Kitamura, S. A1-5
Kitamura, S. A5-5
Kiyasu, S. A4-4
Kobayashi, H. A4-2
Koga, M. B6-3
Kokaji, S. C1-1
Kondo, T. B3-1
Kuboshiki, S. B1-6
Kurematsu, Y. A1-5
Kurokawa, H. C1-1
Kyuma, K. A4-1
Kyura, N. B5-2
Langton, C. G. PS-1
Lee, J. J. A2-1
Lee, J. J. B6-2
Lee, J. J. C1-2
Lee, J. J. B2-3
Lee, J. J. B3-5
Lee, S. W. B6-4
Li, X. A4-6
Liu, Y. C1-5
Looney, C.G. A3-5
Mabuchi, T. B3-6
Matsumoto, T. A4-2

Miura, H. PS-2
Murao, H. A5-5
Murata, J. B6-3
Murata, J. B1-3
Murata, S. C1-1
Musya, T. PS-1
Nagasawa, T. B3-6
Nagata, T. C1-3
Nakamura, A. B5-1
Nakamura, M. B5-2
Nishikawa, Y. A2-3
Nonaka, T. B2-5
Nozawa, T. B4-1
Ochiai, S. B2-5
Ochiai, T. B3-2
Ogasawara, T. B5-1
Oguro, R. B2-1
Ohbayashi, M. B6-3
Ohbayashi, M. B1-3
Ohkawa, K. B5-3
Ohnishi, N. A4-5
Ohnishi, N. A1-2
Ohta, J. A4-1
Oka, T. B3-4
Okamoto, M. B2-5
Okuma, S. B3-4
Onat, A. A2-3
Onitsuka, T. C1-3
Park, K.B. B2-3
Pfeifer, R. B5-4
Rasmussen, S. PS-5
Ray, T. S. PS-2
Saita, H. B1-5
Sakata, M. A2-6
Sano, M. B1-4
Sasaki, M. A1-4
Sato, M. A5-3
Sawada, Y. B1-4
Shao, H. A3-4
Shibata, T. B5-3
Shim, H. S. B6-4
Shimohara, K. A5-2
Shiraki, K. B3-6
Suehiro, T. B5-1
Sugawara, K. B1-4
Sugie, N. A4-5
Sugisaka, M. A4-6
Sugisaka, M. B3-5
Sugisaka, M. A2-2
Sugisaka, M. A2-4
Suzuki, T. B3-4
Suzuki, Y. A1-3
Takata, H. B2-1
Takeda, H. A5-3
Tanaka, H. A3-3
Tanaka, H. A1-3
Tanaka, K. A4-2
Tanie, K. B5-3
Tominaga, D. B2-5
Tomita, K. C1-1
Tsuchiya, K. B2-4
Tsuji, T. B2-1
Tsujita, K. B2-4
Tsukune, H. B5-1
Tsumashima, T. A4-3
Tsumoto, S. A3-3
Tsumoto, S. A1-3
Uchikawa, Y. B3-3
Uchikawa, Y. A3-1
Uchikawa, Y. C1-4
Uchikawa, Y. B1-6
Uchikawa, Y. B3-1
Ueno, S. B4-4
Umeda, N. B2-1
Wang, A.P. B4-4
Wang, H. B3-2
Wang, X. A3-4
Wang, X. B3-5
Wang, Y. B2-6
Watanabe, Y. C1-4
Watanabe, Y. B3-1
We, K.L. B4-1
Yagi, T. A4-2
Yamada, T. B3-6
Yamakawa, T. B6-1
Yamamoto, H. B2-2
Yao, X. C1-5
Yashima, Y. A2-5
Yoshikawa, T. B3-3
Zha, H. B. C1-3
Zhang, Y. G. A4-6