INTELLIGENT SYSTEMS

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Architecture, Design, and Control

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To the memory of our parents

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PREFACE

INTELLIGENCE AS A TOOL OF EVOLUTION

About 600 million years ago, there was an unusual explosion in the biosphere of the earth. Biologists call it the *Cambrian explosion*. The amount and diversity of living creatures that emerged during the Cambrian explosion far exceeded anything that happened before or after this unusual period in the ecological history of the earth. A comparison with the middle part of the sigmoidal[1] curve is a suggestive metaphor for the Cambrian explosion although it leaves more to our imagination rather than offering any explanation of what happened.

The famous scientist S. Gould made an interesting observation:

> The world of life was quiet before and it has been relatively quiet ever since. The recent evolution of consciousness must be viewed as the most cataclysmic happening since the Cambrian if only for its geological and ecological effects. Major events in evolution do not require the origin of new designs. The flexible eucaryotes[2] will continue to produce novelty and diversity so long as one of its latest products controls itself well enough to assure the world a future.[3]

Undoubtedly, the latest products of evolution are we, the people. We are the products who must control ourselves well. This is why the evolution of consciousness happened; it is supposed to *assure the world a future*. S. Gould made an interesting observation: We might not see new evolutionary designs. Apparently, the richness, flexibility, and inventiveness of our brain would compensate for the absence of new evolutionary designs. The brains of living creatures, even in their rudimentary form, guide them toward development of new designs for the evolution (our thoughts, plans, inventions, visual arts, music, and poetry).

Evolution and intelligence are the major known tools in producing a beneficial response to anything that may happen to a living creature. They help the creature survive in most situations, expected and unexpected. Here we should proceed with caution: The concept of the *expected event* presumes a creature that can have expectations. Evolution

[1] *Sigmoidal curve* describes processes that initially grow slowly, then gradually accelerate, achieving a rapid rate of growth, and then slow down, gradually achieving the end with a very low rate of growth.

[2] Eucaryotes are multichromosome living cells, as opposed to procaryotes that are single-chromosome cells.

[3] Stephen Jay Gould, *Ever Since Darwin: Reflections in Natural History*, Norton & Company, New York, 1977, p. 118.

works to the benefit or the successful outcome for a *species*; the idea of expectation in this case is at least puzzling. The idea of the *benefit* or the *success* is puzzling as well. Yes, the need for survival is well known. But what is the source of this need? Even more difficult is the idea of *success*. The latter presumes a *goal*. It is customary to link the goal with intelligence, but what might be the goal of the evolution?

Well, *evolution* and *intelligence* have something very important in common. Both affect our lives the most, and yet both are understood the least.

WE ARE THE TOOLS OF OUR INTELLIGENCE

Certainly, the productivity of design,[4] provided by the old chromosome-based mechanism, has its limitations. It achieved its peak at the time of the Cambrian period, and now, as our brain takes over, a new explosion is on the way. The intricacy of our brain navigates unexpectedly the subtle processes of decision making, beyond this organ's presently known capabilities, with its slow wetware-based neurons placed into an unreliable body prone to hedonism and addictions. In a hectic outburst of events compressed into one century, the brains of mankind have created a surprising engineering phenomenon: *intelligent systems*, which can work for their evolution much more efficiently than we, the people, can.

This thought is intuitively acceptable for those of us who continue researching the surrounding reality even after graduation. Computer-aided design and data mining are not buzzwords anymore; there are innovations actually produced by machines. The decision-making role of all-pervasive automated machines and various software packages is a fact of our lives. This is what happens—automation is coming to the domain of decision making rapidly and maybe even faster than it conquers the area of menial works. (This might be an alarming sign, but it is probably linked with the surprising fact that the market still creates more opportunities for menial jobs than for decision making.)

Evolution, until now the unchallenged domain of living organisms, may soon become possible for robots as well. A computer-based form of evolution—nature's own design strategy—has succeeded in designing LEGO structures without any assistance from humans, by the virtue of learning (Brandeis University). A human-like robot follows passersby with its eyes; a robot-drummer entertains the public (MIT). A robot-vehicle recognizes the edge of the road (Carnegie Mellon). A dune-buggy, controlled by the planner-navigator-pilot hierarchy, travels via cluttered environment by trial-and-error to the goal, then returns much faster because it had already seen the environment, remembered it, and planned a better motion trajectory (Drexel University). Autonomous vehicles can move with no human help at a speed of 55 mph on a highway (Universität der Bundeswehr, München, Germany). A squad of autonomous vehicles travels cooperatively at a speed of 20 mph in a cross-country environment (National Institute of Standards and Technology). Robotic brains can control manipulators, allowing them to carry heavy things cooperatively, not to speak about playing ping-pong which was already achieved years ago. These are mankind's first successful leaps from the early concepts of decision making based on expert systems into the futuristic realm of multiresolutional thinking.

[4]Naturally, we talk about design of a living creature. Evolution is interpreted frequently as a mechanism for designing the living creature. Probably, *self-design* is meant.

THE MOLECULE OF INTELLECT OR EVEN LIFE

It is not so difficult to discover that both evolution and intelligence use the same set of techniques: Both transform real experiences into symbolic representation and keep the messages in a well-organized, computationally efficient form; use these messages for searching groups of similarity and generalizing them; repeat this generalization recursively so that the nested hierarchies of efficiently organized information are being developed; increase their efficiency by focusing attention upon limited subsets of information; and use searching processes to combine elements of this information into messages that could not be obtained from the experiences.

Compact packages of operators, comprising of "grouping-focusing attention-combinatorial search" triplets in various combination, consume the arriving information and transform it into multiresolutional architectures. A simple feedback loop well known from the views of cybernetics could not be decisive in explaining the phenomena of the mind. In this book, we demonstrate that metaphorically speaking, the decision-making processes are realized via distributing the feedback loop over the multiresolutional architecture of information. Or even more accurately, via imposing the multiresolutional architecture upon the feedback mechanism. This is how the mind was built through the history of its development. This is how the model of mind is visualized by the authors of this book.

MULTIRESOLUTIONAL MIND

The concept of multiresolutional (multiscale, multigranular) information representation is the most formidable insight of the mankind in a rush to design new tools for a further leap in the process of evolution. People always distinguish between actual view and the bird's-eye view; smaller picture and larger picture; and the faraway look and close-up. This is the century when we have eventually discovered that our mind uses views of different granularity and scale for the benefits of decision making. This book demonstrates how people employ multiresolutional representations and make decisions of different resolutions.

This concept came simultaneously from different communities and appeared in different disguises. Researchers in computer vision discovered pyramidal image representation. Fractal people recognized this multiscale key to information representation as a mechanism of the construction of nature. European scientists made multigranular representation a part of their new science "synergetics." Practical engineers employed it within "finite element method." Mathematicians have not yet succeeded in unlocking the mystery hidden in *nonstandard analysis*.[5] However, they successfully use many levels of resolution as a practical method of solving partial differential equations ("multigrid methods").

The multiscale habits of thinking reveal something about the architecture of the human mind. Authors are convinced that the key issues of the "mind-design" can be resolved only by restoring the mind's structure in a multiresolutional fashion. Although we cannot observe or touch the structure of our mind, we have to restore it from watching the records of its multiscale functioning. This process of top-down/bottom-up

[5]Nonstandard analysis, a domain of logic discovered by A. Robinson, contemplates the possibility of a noncontradictory bridge between the continuous and discrete mathematics.

restoration of things that cannot be available to our immediate observation is similar to *reverse engineering*. (This term can be found in the 1993 documents[6]; in the context of cognitive science, it was used by D. Dennett[7].)

The results of mind restoration in the form of multiresolutional models described in this book allow for constructive understanding and simulation of our cognitive processes. In addition, multiresolutional models can be used for constructing and exploring machines and organizations that we call *intelligent systems*. Intelligent systems mimic human abilities to perceive the world, to collect and organize knowledge, to imagine things and make plans about them, to execute these plans and control ourselves. Remember that if we are able to control ourselves well enough, we may *assure the world a future*.

So far, we have been successful in inventing what has already been invented by nature. Computer scientists, with biologists, have succeeded in simulating the processes of the evolution of eye as an organ, and with engineers, have analyzed the process of evolving robotic skills of building bridges. In hindsight, the algorithm for discovery of sophisticated engineering devices turned out to be very simple. In reality, it took many centuries for humans to capture the skills of engineering design, develop rational plans of actions that take planners weeks to design, and compute trajectories of motion that require engineers hours to design.

ABOUT THIS BOOK

This book is about robotic brains as they should be designed and implemented in the very near future. The biologists and psychologists will find the engineering views on cognitive processes in human brain. Also, they can find numerous suggestions from two engineers on how they should understand human brains. Engineers should consider these suggestions as engineering metaphors. However, in the engineering part, the book contains the outcomes of many years of experience in engineering design and industrial implementation. Several doctoral and masteral theses were developed under the guidance of the authors; the essence of these researches was included in the book. The authors have merged together the results of their research obtained for the last 15 years. Some of these results happen to coincide, and they were very persuasive for the authors. Part of its materials precipitated from working together since 1994.

Our engineering recommendations are verified by implementing them in a realistic environment. Indeed, multiresolutional representation reduces the complexity of computation. Planning can be applied as a nested search process at all levels of resolution. Elementary loop of functioning must be specified for all levels of resolution before we start other engineering activities; a lot of time and money will be saved. Multiple levels of resolution can work jointly and coherently.

This book is intended to serve as a textbook for graduate courses in various disciplines: engineering (including robotics, mechatronics, and automatic control), business management, computer and information science. However, we would expect that cognitive scientists, psychologists, and biologists will benefit in using this as a text, too. Quiz and test problems are included at the end of each chapter.

[6]See a legal document in URL http://www.lgu.com/cr46.htm

[7]D. Dennett, Cognitive science as reverse engineering, in *Brainchildren, Essays on Designing Minds*, MIT Press and Penguin, 1998.

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The book is illustrated by the results of application of the new theory for equipping numerous intelligent machines, including industrial robots and autonomous vehicles. We did not address several important issues related to intelligence, like natural language understanding. However, our methodology is expected to be instrumental in this case, too.

In the last 15 years or so, we have worked on these issues in close cooperation. We achieved the highest level of mutual understanding, and it would be very difficult to determine who wrote what in this book. Nevertheless, even this level of cooperation would be insufficient for preparing the manuscript without help and contribution from our colleagues (in alphabetical order): U. Bar-Am, R. Bhatt, S. Bhasin, R. Bostelman, D. Coombs, N. Dagalakis, S. Drakunov, P. Filipovich, D. Gaw, G. Grevera, T. Hong, J. Horst, H.-M. Huang, A. Jacoff, E. Koch, a. Lacaze, S. Legowik, E. Messina, M. A. Meystel, J. Michaloski, Y. Moscovitz, K. Murphy, M. Nashman, R. Nawathe, L. Perlovsky, F. Proctor, I. Rybak, W. Rippey, H. Scott, S. Szabo, C. Tasoluk, and S. Uzzaman. We thank all of them for their constant and continuous support in the past 10 to 15 years.

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