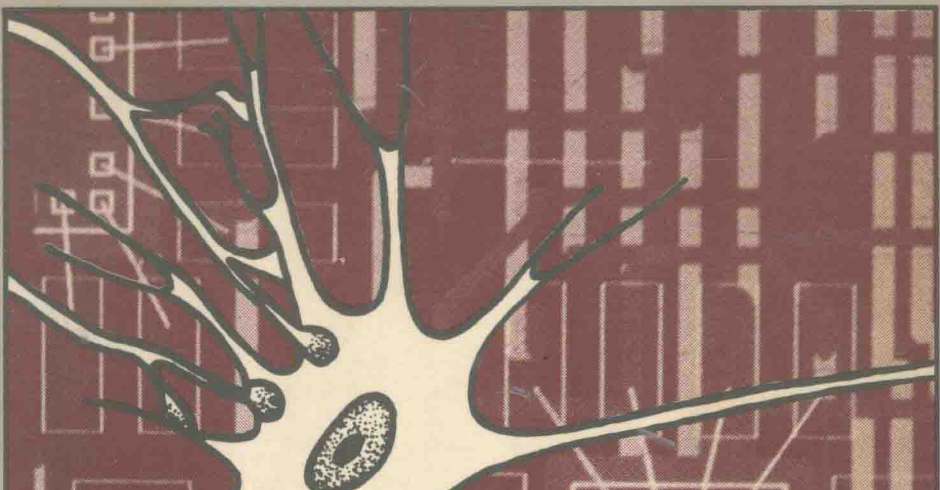
BIOCOMPUTERS

THE NEXT GENERATION FROM JAPAN



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Chapman and Hall

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Translator's preface

The editors of *Biocomputers*, Tsuguchika Kaminuma and Gen Matsumoto, shun the 'sixth generation' label for the biocomputing revolution and prefer to emphasize the fact that certain qualitative changes in the nature of computing are underway. Nevertheless, as imprecise as such generational categories are, it is likely that the 'sixth' label will stick – merely as a convenient marker to identify the leap from a silicon-based technology to the various carbon-based organic technologies which are at the heart of biocomputing. There are of course various criteria upon which to determine the 'generation' of a particular computer configuration, but the so-called Fifth Generation Project in Japan has firmly attached the 'fifth' label to silicon-based inference machines having limited parallel processing capabilities. Further growth in those directions is likely, but the inauguration of a new generation requires a qualitative change to justify the new label. A switch to components which contain organic molecules would certainly justify the 'sixth' label.

On the other hand, 'neurocomputing' does not fall obviously within any particular generation. It is, broadly, an attempt to mimic or simulate in computers the kinds of operations that real brains perform. As such, neurocomputing can be done on computers of the third to sixth generations, whether serial or parallel, silicon- or carbon-based. Neurocomputing does, however, have deep connections with biocomputing in so far as the hardware and/or software design of neurocomputers is explicitly based upon principles of organization found to work in living brains. For this reason, neurocomputing – in the sense used by Kaminuma and Matsumoto – is often referred to as a field within biocomputing.

Particularly as silicon-based dedicated neurocomputers are developed for neural net style computing (the connectionist machines), the structural similarities between neurocomputers and third or fourth generation computers will be overshadowed by their functional differences. The structural gap between neurocomputers and biocomputers will remain, however, in so far as neurocomputers are silicon computers which have architectural or software principles borrowed from the brain, whereas biocomputers will have at least some organic hardware similarities with living nervous systems. In other words, regardless of whether or not biocomputing is synonymous with the sixth generation, biocomputing is conceptually a large step beyond the most optimistic ideas about successful fifth generation machines.

There is another sense in which biocomputing can be thought of as a new generation of computing. As mentioned by several authors in the chapters that follow, massive parallel processing, which will make rapid pattern recognition and manipulation of a large volume of analog data possible, is generally thought to be one of the principal strengths of the information processing done by the right cerebral hemisphere in man. If the fifth generation computers, with their logical, symbolic and language processing capabilities, can be thought of as artificial 'left hemispheres', certainly biocomputers can be considered to be artificial 'right hemispheres'.

Even assuming the success of these computing projects in capturing the essentials of left and right hemisphere functions, what will remain for neuroscience and computing to achieve will be (a) an understanding and (b) the technological implementation of mechanisms for the integration of those two 'hemispheres' or modes of information processing. It is a remarkable fact that the largest nerve tract in the human brain, the corpus callosum, connects the two cerebral hemispheres. It is also known to show more rapid evolutionary enlargement than even the cerebral cortex. These anatomical facts suggest that the coordinated interaction of the left and right sides of the nervous system across this tract is not a triviality, but may well be an important issue in the unravelling of the 'brain code' (Cook, 1986). Similarly, the task of getting fifth and sixth generation systems (or, alternatively, silicon- and carbon-based components) to 'talk' with one another is likely to require a significant effort.

Interesting developments within the realm of fifth generation computing continue to be reported. New expert systems, particularly in scientific fields, are appearing regularly, PROLOG has become a relatively popular programming language (Mizoguchi, 1990), natural language processing is becoming far more sophisticated, and machine translation systems are now available at the personal computer level in Japan (Nagao, 1989). As noted by Kaminuma and Matsumoto, however, these developments alone have not – and probably cannot – cross the threshold into creativity and higher-level cognitive processing.

Whatever the actual mechanisms used by the human brain in integrating and synthesizing the information of the two cerebral hemispheres and in achieving higher-level cognition, it is clear that the coordination of symbolic processes (language) with analogical data processing is not a topic that can be relegated to a mere footnote in neuroscience or be considered as a minor, single-channel connection between the fifth and sixth generation computers. There is apparently room for the development of one further generation (the seventh?) before we have computers which realistically mimic the integrated functioning of the bilateral human brain.

In any case, at least one 'generation' following the fifth generation computers is well on its way and is best described with the word 'biocomputer'. The discoveries and insights which underlie biocomputing have originated in universities and private industry throughout the world, but interest and capital investment is rapidly intensifying in Japan. This is evident in the Japanese media – with many books and magazines devoted to topics on neural nets, neurocomputing and biocomputing. More significantly, however, following the organization of the fifth generation project by the Ministry of International Trade and Industry (MITI), the same governmental agency has again organized two ten-year research projects aiming in the direction of biocomputing. The first to be funded was a biodevice project and the second is the biocomputer project to be funded for a decade starting in 1990. Progress in these and other fields of computing continues to occur at a rapid pace throughout the world; the present book represents an up-to-date view of current interest in Japan by nine senior figures in this field.

Among the various themes which recur in the chapters of this book, the following are particularly noteworthy. (i) There is a structural and functional unit of the cerebral cortex which is larger than the single neuron – that is, the cortical column containing several hundred to several thousand neurons. (ii) Simulated neural nets which also contain only several hundreds of artificial 'neurons' can already perform useful computations in physiologically semi-realistic ways. (iii) The sixth generation of computers must embody not only the logical inference mechanisms of fifth generation computers, they must also embody 'right hemisphere-like' capabilities – including analog data processing, creativity, emotion and perhaps even the subconscious mind.

Taken together, these themes suggest an interesting possibility in the development of a biologically-motivated computer architecture. That is, consider a neurocomputer which has linked coprocessors – where one of the two processors is specialized for the (left hemisphere-like) logical, symbolic operations, on the one hand, and the other is specialized for the (right hemisphere-like) processing of the context, higher-order implications, and logically less-precise connotations of the information simultaneously processed in the other processor. Such a linked coprocessor architecture would mimic the overwhelmingly-dominant bilateral organization of the animal (and, most importantly, the human) nervous system and would deal at a relatively microscopic level with the problem of the coordination between two complementary modes of thought. In such a view, the first task in developing a neurocomputer which mimics the human brain is the design of coprocessors with complementary functions, and only subsequently the linking together of large numbers of such coprocessors. In other words, before attacking the n-processor problem for massive parallel processing, the design of complementary coprocessors should be attacked – and then the n-coprocessor problem addressed.

The tone of the book is somewhat pessimistic with regard to the future of computing using silicon components without massive parallelism, but the editors are particularly optimistic about both the technological capacities and the humanistic applications of biocomputing once new carbon-based technologies are more fully developed. More speculatively, but ultimately of even greater interest, is the editors' contention that biocomputing is inherently linked to the technology of producing 'artificial life'. In other words, the deeper understanding of cellular mechanisms which will allow the exploitation of the molecules of life in biocomputers will inevitably be used to manipulate life forms to a far greater extent than is now possible in biotechnology. This kind of 'artificial intelligence' holds much greater potential for exploring and possibly altering the evolution of biological forms and is perhaps a more controversial topic and perilous adventure than biocomputers themselves.

Norman D. Cook, Zurich

Preface

The words 'biocomputer' and 'biocomputing' have recently come into use both in the life sciences and the computer sciences. Being involved in such research, we have felt the need to explain what is meant by 'biocomputing', and how 'biocomputers' differ from previous computers. Some enthusiasts ask if biocomputers are the 'sixth generation' computers to follow the fifth generation still under development. Frankly, we do not believe such labels are particularly meaningful since so many questions remain unanswered about the future directions in which biocomputers will be developed. The mechanisms implied by the 'bio' in biocomputing certainly are those found in biological organisms, particularly those in brains and nervous systems, but we still do not understand the underlying engineering principles of brains and do not know methods for their technological exploitation.

We nevertheless do know that one of the major trends in science and technology today is aimed at the biocomputer. Briefly, the biocomputer is a computer which contains characteristics of both current computers and living organisms. Three major approaches toward the construction of biocomputers are in evidence (Kaminuma, 1985a, 1985b).

1. The study of the mechanisms of biology, particularly those of the living brain, and the use of those results in the redesign of the software and of the hardware architecture of computers based upon semiconductor technology.
2. The development of biocomponents which are similar to and/or made of biological macromolecules, then the development of biochips which make use of those components, and ultimately the construction of biocomputers.
3. The development of techniques for artificially creating life, and then the utilization of the mechanisms of ontogeny or evolution in the development of computers with artificial intelligence or, perhaps, ultra-human intelligence.

In response to the first approach to biocomputing, the objection could be raised that it does not differ significantly from a variety of previous approaches which have been suggested over previous decades, such as bionics. With regard to the second approach, it could be argued that biochips and even biocomputers might be possible, but that does not necessarily mean that such machines will be significantly more powerful than today's computers. And in response to the 'artificial life' approach, it might well be said that as a consequence of our profound ignorance of what life is, such developments will remain impossible for the rest of this century and well beyond – and indeed very real ethical, if not technological, problems must be faced.

Why, in any case, must we incorporate biological and even brain characteristics into today's computers? The answer is that we believe that it is desirable for a host of reasons to produce computers with capabilities vastly superior to those of current computers, and that one road toward improvements of this kind is the close imitation of biological systems which display those capabilities. Such capabilities include fine-grained mechanical control, much sharper and faster pattern recognition, the capacity for flexible and intelligent interaction with human beings, and high-level reasoning capabilities which even surpass the best human specialists.

It might, of course, be asked whether or not such functions could be attained in current large-scale computer projects – such as those in progress in supercomputing and parallel processing logical inference computers (the so-called fifth generation computers). The answer is both yes and no. Since computer capabilities are all relative to the processing of other systems, it is hard to imagine that, in principle, there are any functions which absolutely can or cannot be achieved within any given technology. Nevertheless, of all the research and development plans of current projects, none are aiming at realization of cognitive functions comparable to human intelligence, or at the flexible and detailed information processing of living organisms. Moreover, none are devoted to implementing uniquely biological functions, such as the ability to discover and fix defects or identify and correct mistakes. Moreover, the quintessentially biological functions of living forms, that is, autonomy, self-organization, self-replication and development – as witnessed both in evolution and in individual ontogeny – are completely absent from current computing machines.

In a word, biocomputing is aimed at the technological realization of various biological characteristics which are missing in today's computers. But can such an attempt succeed as an extension of modern semiconductor technology? Or will it be necessary to use fundamentally new techniques for constructing artificial biological systems – techniques for incorporating biological structures and, in some cases, for making use of biological materials. If the latter is the case, then it will be necessary to employ so-called bioengineering techniques which differ fundamentally from present-day electronics techniques. In such a scenario, biocomputing will be a discipline which touches on a wide range of scientific fields. It cannot be said that all the targets of such a wide-reaching discipline fall within the realm of current engineering. But it can be said that there is now some enthusiasm for initiating such research and we believe that, at the very least, the scientific foundations for such research are now being laid.

The 20th century has been an era during which the fundamental laws of physics have been clarified. Those insights have greatly influenced not only the other natural sciences (chemistry and biology), but also the applied sciences of engineering and medicine. Notably, one of the physicists who helped build the foundations of quantum physics, Erwin Schrödinger, spoke of the possibility of new natural laws which were unknown to physics, but which might be involved in the processes of life in his well-known book *What is Life?*, published in 1944. Influenced by that book, many young physicists turned away from basic physics – where many of the fundamental questions concerning the foundations of physical reality had already been answered – and contributed significantly to the building of the foundations of molecular biology.

The more the basic mechanisms of life were clarified, however, the more it was apparent that there were no forces or laws unknown to the physicist. Instead, the mysteries of life were found to reside in the information system now known as the genetic code. Instead of the discovery of unknown 'vital forces', laws were discovered concerning the higher-order informational structure of molecules. In order to understand the dynamic properties of life, biological structures needed to be studied not only as physical objects, but also as informational processes (a view emphasized by Satoshi Watanabe in *Life and Freedom*).

Information science has progressed together with developments in computer science, but such progress has been primarily in mathematical logic and communications engineering rather than in natural science. For information science to develop as a true science, it is essential that it join hands with the life sciences. In so doing, such research will necessarily become the scientific foundations for bicomputing. We anticipate that, in the near future, exchanges between the computer sciences and the life sciences will deepen within a broad scientific discipline of information science.

Biocomputers will be the technological fruit born from the natural fusion of such scientific disciplines. For this reason, we believe that biocomputers are conceptually completely different from the technological developments of all previous computers of whatever 'generation'. Biocomputing involves both fundamental and applied research, and is likely to have a large influence on the directions of a vast range of endeavours in science and technology.

This book is divided into four parts. In Part One, a brief history of computing is given, followed by an explanation of current and new computers. In Part Two, the concepts and developments in the life sciences which form the basis for biocomputers are introduced. In Part Three, we explore ideas concerning biocomputers in relation to the concepts described in Part Two. There we discuss possibilities for so-called biochip computers, neurocomputers and computers with creative intelligence. In the final section, Part Four, we propose a research plan and develop ideas concerning the possible impact of biocomputing. Parts One and Four were written by the editors, and Parts Two and Three were written by various distinguished contributors – as well as by the editors.

We wish to emphasize that particularly Parts One and Four strongly reflect the personal opinions of the editors concerning developments in biocomputing, and those opinions are not necessarily shared by the authors of the other chapters. In other words, each author is to some degree developing his own ideas concerning biocomputers – as indeed we hope the reader will do.

Our main purpose in undertaking the writing of this book has been to communicate to a wide audience – and particularly to young researchers – the recent developments in and the interaction between computing and the life sciences. If we succeed in stimulating the reader's intellectual curiosity and perhaps even stimulate new research activity, we will be delighted.

Finally, we would like to express our thanks to the many people who have allowed us to use diagrams and photographs for this book, and to Mr. Hiroshi Mizuno of Kinokuniya, who has patiently worked behind the scenes on our behalf.

Tsuguchika Kaminuma and Gen Matsumoto, Tokyo

Contents

Part One

Birth of a new discipline: biocomputing