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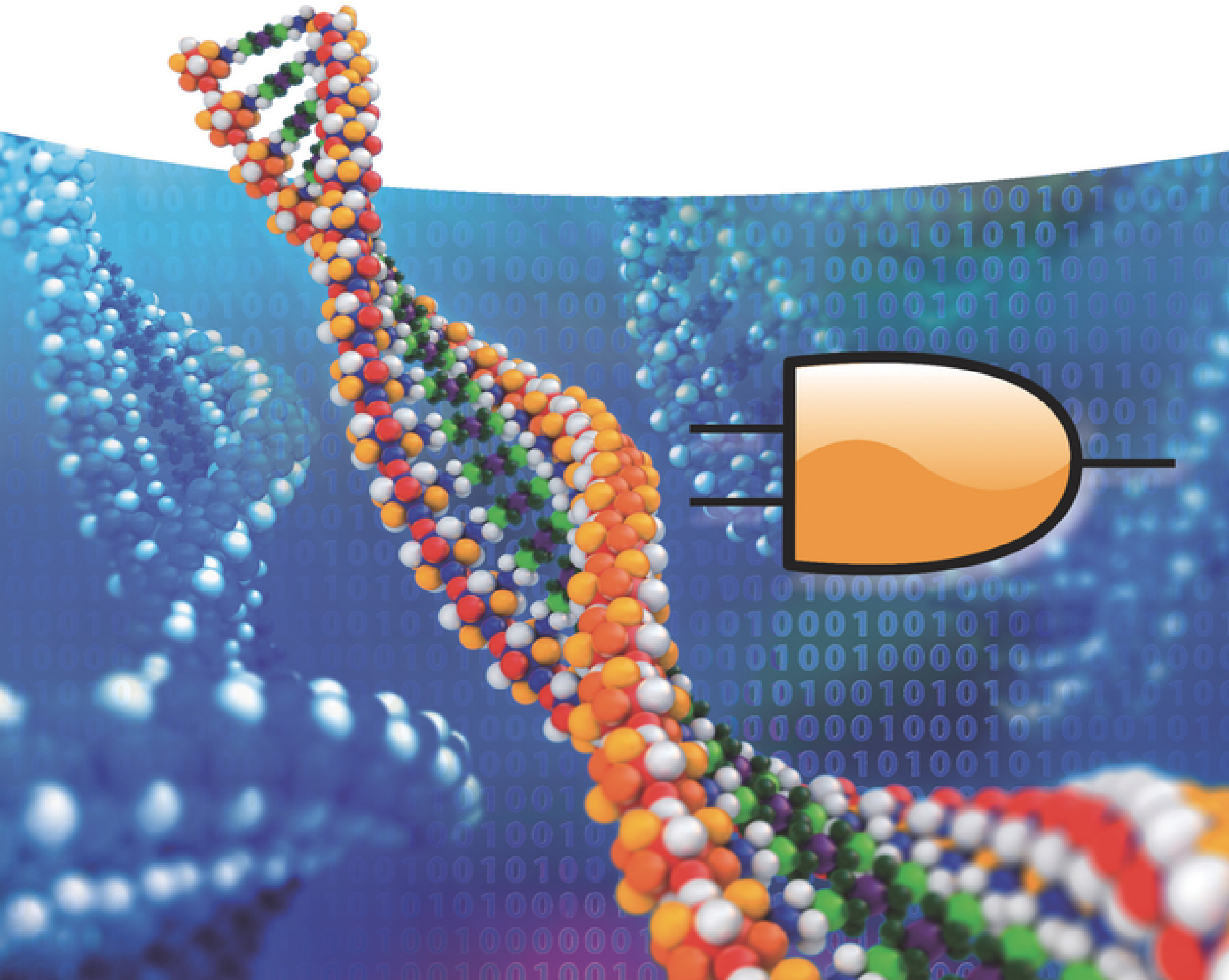
Evgeny Katz

DNA- and RNA-Based Computing Systems



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Preface

The use of biomolecular systems for processing information, performing logic operations, computational operations, and even automata performance is a rapidly developing research area. The entire field was named with the general buzzwords, “biomolecular computing” or “biocomputing.” Exciting advances in the area include the use of various biomolecular systems including proteins/enzymes, DNA, RNA, DNAzymes, antigens/antibodies, and even whole biological (usually microbial) cells operating as “hardware” for unconventional computing. The present book concentrates on DNA and RNA molecules utilized for information processing (biocomputing). Extensive ongoing research in the DNA- and RNA-based biocomputing has been motivated by speeding up computation, at least for solving some special problems, due to massive parallel operation of numerous biomolecules. The advantages of the DNA and RNA computing systems are also in their ability to operate in a biological environment for solving biomedical problems in terms of diagnostics and possibly therapeutic action, operating as nanorobots in living organisms. DNA molecules are also applicable as memory material with extremely high data density storage.

The present book summarizes research efforts of many groups in different universities and countries. The book reviews and exemplifies these developments, as well as offering an outlook for possible future research foci. The various topics covered highlight key aspects and the future perspectives of the DNA- and RNA-based computing. The different topics addressed in this book will be of high interest to the interdisciplinary community active in the area of unconventional biocomputing. The readers can find additional complementary material on molecular [1], biomolecular [2], and enzyme-based [3] computing published recently by Wiley-VCH (see book cover pages below). It is hoped that the present book will be important and beneficial for researchers and students working in various areas related to biochemical computing, including biochemistry, materials science, computer science, and so on. Furthermore, the book is aimed to attract young scientists and introduce them to the field while providing newcomers with an enormous collection of literature references. I, indeed, hope that the book will spark the imagination of scientists to further develop the topic.

I would like to conclude this preface by thanking my wife Nina for her support in every respect in the past 49 years. Without her help it would not have been possible to complete this work. Also, cooperation and hard work of all authors working together with me on this edited volume are highly appreciated.

Potsdam, NY, USA

January 2020

Evgeny Katz

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2 Katz, E. (ed.) (2012). *Biomolecular Information Processing – From Logic Systems to Smart Sensors and Actuators*. Weinheim: Wiley-VCH.

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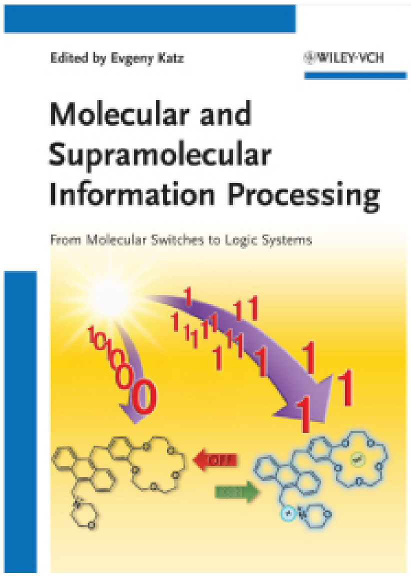

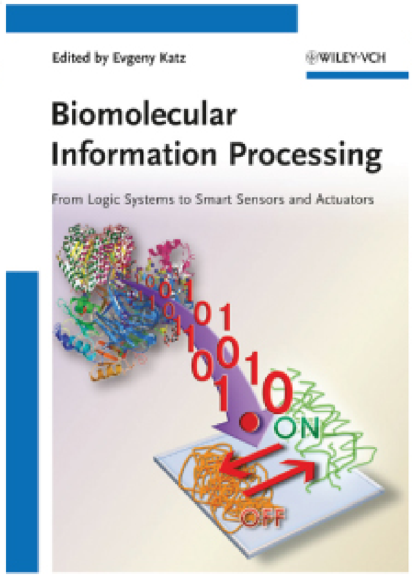

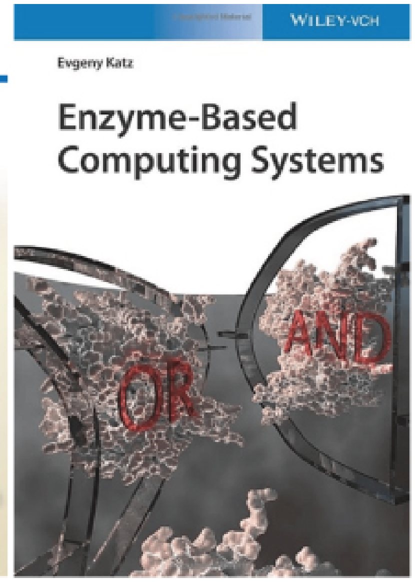

1
DNA Computing: Origination, Motivation, and Goals – Illustrated Introduction

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1.1 Motivation and Applications

Exponential development of computing systems based on silicon materials and binary algorithms formulated as "Moore's law" [1] (Figure 1.1) is coming to the end being limited by further component miniaturization and by the speed of operation. Conceptually novel ideas are needed to break through these limitations. The quest for novel ideas in the information processing has resulted in several exciting directions in the general area of unconventional computing [2–4], including research in quantum computing [5] and biologically inspired molecular computing [6–9]. Molecular computing systems, generally motivated by mimicking natural biological information processing [10,11], are not necessarily based on biomolecules and could be represented by synthetic molecules with signal-controlled switchable properties. Synthetic molecular systems and nano-species have been designed to mimic operation of Boolean logic gates and demonstrate basic arithmetic functions and memory units. However, despite progress achieved in assembling synthetic molecular systems performing basic Boolean operations and simple computations [6–9], these systems have limited complexity, and further increase of their complexity is very challenging.

A new advance in the development of molecular information systems has been achieved with use of biomolecular species [12] (Figure 1.2) such as deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) [13–16], oligopeptides [17], proteins [18], enzymes [2,19,20], antigens/antibodies [21], and even whole biological cells/organisms [22–24] capable of operating in a biological environment [25], borrowing some ideas from systems biology [26]. The advantage of the biomolecular computing systems is their ability to be integrated in artificially designed complex reacting processes mimicking multistep information processing networks. These systems are still far away from the natural information processing in cells but are already much more complex than pure synthetic molecular systems. In fact, biochemical reactions are at the core of the mechanism of life itself, and therefore one could set rather ambitious expectations for how far can (bio)chemical reaction systems be scaled up in complexity, if not speed, for information processing. While in a long perspective a "biocomputer" might become a reality [27], particularly for some special applications, e.g., for solving complex combinatorial problems [28], potentially promising to have an advantage over silicon-based electronic computers due to parallel computing performed by numerous biomolecular units, the present level of technology does not allow any practical use of biomolecular systems for real computational applications. For achieving any practical result soon, some other applications, different from making a biocomputer, should be considered using the (bio)molecular systems with a limited complexity. One of the immediate possible applications for molecular logic systems is a special kind of biosensing [29–31] where the multiple input signals are logically processed through chemical reactions resulting in YES/NO decisions in the binary (**0**,**1**) format. In this subarea of biomolecular logic systems, practical results are already possible at the present level of the system complexity, particularly for biomedical applications [32–35]. Overall, the research in molecular/biomolecular information processing, which has been motivated originally to progress unconventional computing applications, is broadly developing to areas not directly related to computing in its narrow definition. This research is bringing us to novel areas in sensing/biosensing [29–31], switchable "smart" materials controlled by logically processed signals [32–36], bioelectronic devices (e.g., biofuel cells) controlled by external signals [37,38], signal-controlled release processes [39–43], etc.

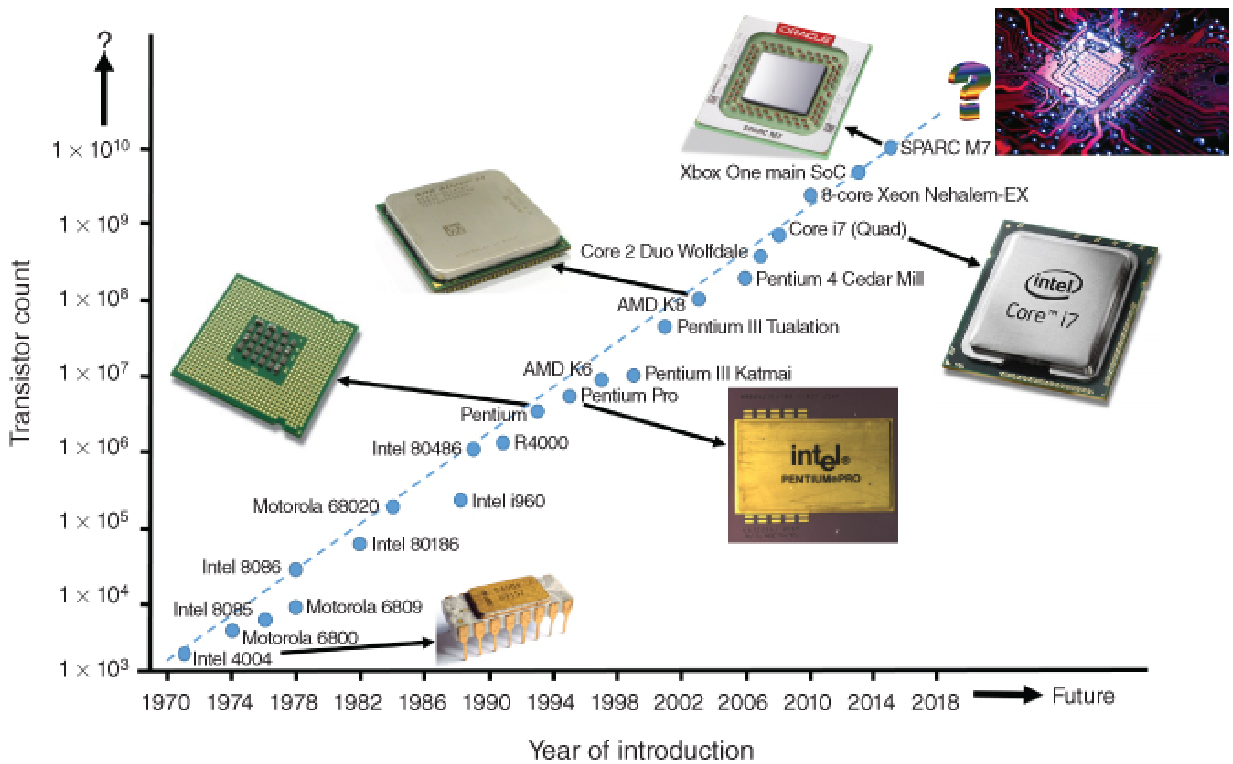

Figure 1.1 Moore's law – exponential increase of transistors on integrated circuit chips. (The plot shown in the figure is based on the data provided by Wikipedia: https://en.wikipedia.org/wiki/Moore%27s_law.)

Source: From Katz [2]. Reprinted with the permission of John Wiley and Sons.

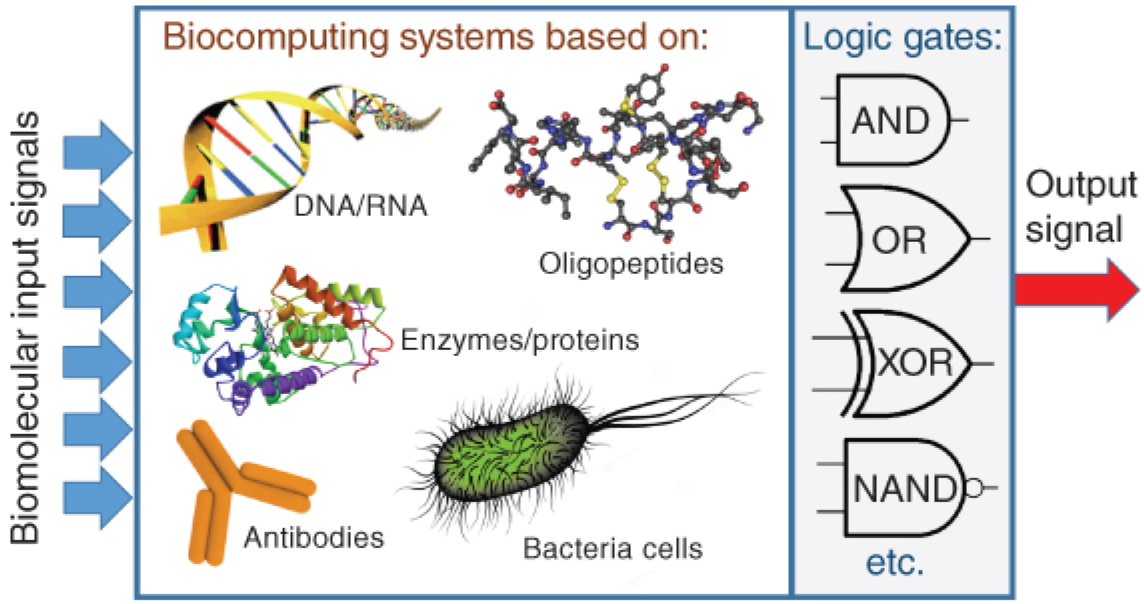

Figure 1.2 Biomolecular computing systems mimicking operation of different Boolean logic gates and circuitries can be based on various species including oligopeptides, enzymes/proteins, DNA/RNA, antibodies, and even whole biological (e.g., microbial) cells.

Source: From Katz 2019 [2], Boolean Logic Gates Realized with Enzyme-Catalyzed Reactions – Unusual Look at Usual Chemical Reactions. ChemPhysChem © 2018. Reproduced with the permission of John Wiley & Sons.

1.2 DNA- and RNA-Based Biocomputing Systems in Progress

While the general topics of the biomolecular computing [12] and specifically the enzyme-based computing [44] have been covered with recently published books, the present book is concentrated on the use of DNA and RNA molecules in computing systems, broadly defined as information processing systems. From the time (1953) when James D. Watson and Francis H.C. Crick (Figure 1.3) discovered chemical structure of DNA (Figure 1.4) [45], the progress in the DNA study resulted in many novel fundamental scientific concepts [46–48] and highly important practical