

Edited by
Evgeny Katz

DNA- and RNA- Based Computing Systems

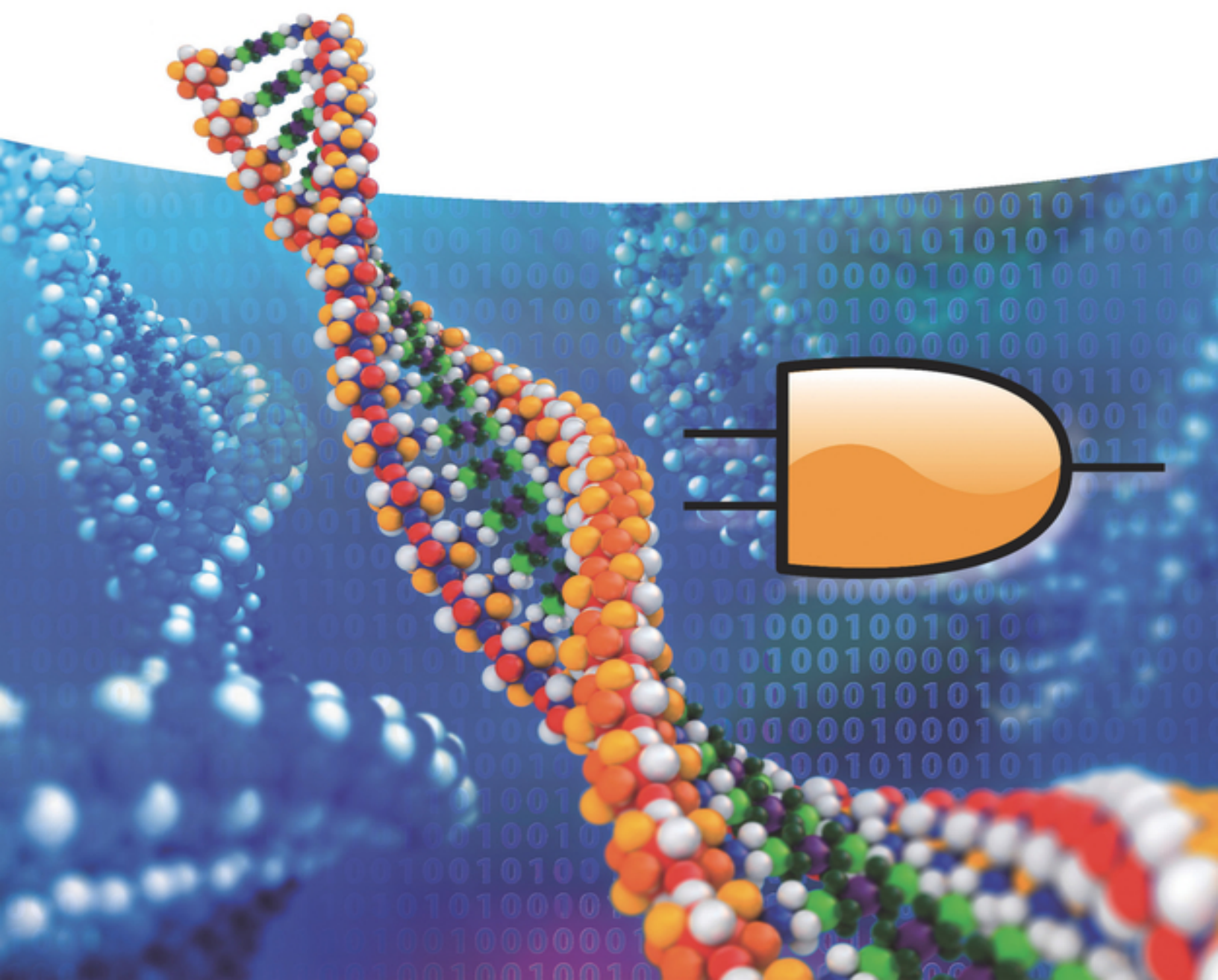


Table of Contents

[Cover](#)

[DNA- and RNA-Based Computing Systems](#)

[Copyright](#)

[Preface](#)

[References](#)

[1 DNA Computing: Origination, Motivation, and Goals – Illustrated Introduction](#)

[1.1 Motivation and Applications](#)

[1.2 DNA- and RNA-Based Biocomputing Systems in Progress](#)

[1.3 DNA-Based Information Storage Systems](#)

[1.4 Short Conclusions and Comments on the Book](#)

[References](#)

[2 DNA Computing: Methodologies and Challenges](#)

[2.1 Introduction to DNA Computing Methodologies](#)

[2.2 Key Developments in DNA Computing](#)

[2.3 Challenges](#)

[Acknowledgment](#)

[References](#)

[3 DNA Computing and Circuits](#)

[3.1 From Theory to DNA Implementations](#)

[3.2 Application-Specific DNA Circuits](#)

[Acknowledgments](#)

[References](#)

[4 Connecting DNA Logic Gates in Computational Circuits](#)

[4.1 DNA Logic Gates in the Context of Molecular Computation](#)

[4.2 Connecting Deoxyribozyme Logic Gates](#)

[4.3 Connecting Gates Based on DNA Strand Displacement](#)

[4.4 Logic Gates Connected Via DNA Four-Way Junction \(4WJ\)](#)

[4.5 Conclusion](#)

[References](#)

[Note](#)

[5 Development of Logic Gate Nanodevices from Fluorogenic RNA Aptamers](#)

[5.1 Nucleic Acid: The Material of Choice for Nanotechnology](#)

[5.2 RNA Aptamers are Modular and Programmable Biosensing Units](#)

[5.3 Construction of RNA Nanoparticles with Integrated Logic Gate Operations Using Light-Up Aptamers](#)

[5.4 Conclusion](#)

[Acknowledgments](#)

[References](#)

[6 Programming Molecular Circuitry and Intracellular Computing with Framework Nucleic Acids](#)

[6.1 Framework Nucleic Acids](#)

[6.2 A Toolbox for Biomolecular Engineering of Living Systems](#)

[6.3 Targeted Applications](#)

[6.4 Nucleic Acid Nanotechnology-Enabled Computing Kernel](#)

[6.5 I/O and Human-Computer Interfacing](#)

[6.6 Information Storage](#)

[6.7 Perspectives](#)

[6.8 Conclusion](#)

[References](#)

[7 Engineering DNA Switches for DNA Computing Applications](#)

[7.1 Introduction](#)

[7.2 Selecting Recognition Element Based on Input](#)

[7.3 Engineering Switching Mechanisms](#)

[7.4 Engineering Logic Output Function Response](#)

[7.5 Optimizing Switch Response](#)

[7.6 Perspective](#)

[Acknowledgments](#)

[References](#)

[8 Fluorescent Signal Design in DNA Logic Circuits](#)

[8.1 Basic Signal Generation Strategies Based on DNA Structures](#)

[8.2 Designs for Constructing Multi-output Signals](#)

[8.3 Summary and Outlook](#)

[References](#)

[9 Nontraditional Luminescent and Quenching Materials for Nucleic Acid-Based Molecular Photonic Logic](#)

[9.1 Introduction](#)

[9.2 DNA Molecular Photonic Logic Gates](#)

[9.3 Nontraditional Luminescent Materials](#)

[9.4 Semiconductor “Quantum Dot” Nanocrystals](#)

[9.5 Lanthanide-Based Materials](#)

[9.6 Gold Nanoparticles](#)

[9.7 Metal Nanoclusters](#)

[9.8 Carbon Nanomaterials](#)

[9.9 Conjugated Polymers](#)

[9.10 Conclusions and Perspective](#)

[References](#)

[10 Programming Spatiotemporal Patterns with DNA-Based Circuits](#)

[10.1 Introduction](#)

[10.2 Experimental Implementation of DNA Analog Circuits](#)

[10.3 Time-Dependent Spatial Patterns](#)

[10.4 Steady-State Spatial Patterns](#)

[10.5 Conclusion and Perspectives](#)

[Acknowledgments](#)

[References](#)

[11 Computing Without Computing: DNA Version](#)

[11.1 Introduction](#)

[11.2 Computing Without Computing – Quantum Version: A Brief Reminder](#)

[11.3 Computing Without Computing – Version Involving Acausal Processes: A Reminder](#)

[11.4 Computing Without Computing: – DNA Version](#)

[11.5 DNA Computing Without Computing Is Somewhat Less Powerful than Traditional DNA Computing: A Proof](#)

[11.6 First Related Result: Security Is More Difficult to Achieve than Privacy](#)

[11.7 Second Related Result: Data Storage Is More Difficult than Data Transmission](#)

[Acknowledgments](#)

[References](#)

12 DNA Computing: Versatile Logic Circuits and Innovative Bio-applications

12.1 Definition, Logical Principle, and Classification of DNA Computing

12.2 Advanced Arithmetic DNA Logic Devices

12.3 Advanced Non-arithmetic DNA Logic Devices

12.4 Concatenated Logic Circuits

12.5 Innovative Multifunctional DNA Logic Library

12.6 Intelligent Bio-applications

12.7 Prospects

Acknowledgment

References

13 Nucleic Acid-Based Computing in Living Cells Using Strand Displacement Processes

13.1 Nucleic Acid Strand Displacement

13.2 Synthetic Riboregulators

13.3 Combining Strand Displacement and CRISPR Mechanisms

13.4 Computing Via Nucleic Acid Strand Displacement in Mammalian Cells

13.5 Outlook

References

14 Strand Displacement in DNA-Based Nanodevices and Logic

14.1 An Introduction to Strand Displacement Reactions

14.2 Dynamic Reconfiguration of Structural Devices

14.3 Stepped and Autonomous DNA Walkers

14.4 Early Breakthroughs in DNA Computing

14.5 DNA-Based Molecular Logic

[14.6 Future Prospects for Strand Displacement-Based Devices](#)

[Acknowledgment](#)

[References](#)

[15 Development and Application of Catalytic DNA in Nanoscale Robotics](#)

[15.1 Introduction](#)

[15.2 Brief History of DNAzymes](#)

[15.3 Experimental Implementations](#)

[15.4 DNAzyme Walkers](#)

[15.5 Statistical Mechanics and Simulation](#)

[15.6 Conclusions](#)

[References](#)

[16 DNA Origami Transformers](#)

[16.1 Introduction](#)

[16.2 Design](#)

[16.3 Experimental Demonstrations](#)

[16.4 Applications](#)

[16.5 Conclusion](#)

[Acknowledgment](#)

[References](#)

[17 Nanopore Decoding for DNA Computing](#)

[17.1 Introduction](#)

[17.2 Application of Nanopore Technology for Rapid and Label-Free Decoding](#)

[17.3 Application of Nanopore Decoding in Medical Diagnosis](#)

[17.4 Conclusions](#)

[References](#)

[18 An Overview of DNA-Based Digital Data Storage](#)

[18.1 Introduction](#)

[18.2 Components of a DNA Storage System](#)

[18.3 Conclusions and Outlook](#)

[Acknowledgments](#)

[References](#)

[19 Interfacing Enzyme-Based and DNA-Based Computing Systems: From Simple Boolean Logic to Sophisticated Reversible Logic Systems](#)

[19.1 Interfacing Enzyme-Based and DNA-Based Computing Systems is a Challenging Goal: Motivations and Approaches](#)

[19.2 Bioelectronic Interface Transducing Logically Processed Signals from an Enzymatic System to a DNA System](#)

[19.3 The Bioelectronic Interface Connecting Enzyme-Based Reversible Logic Gates and DNA-Based Reversible Logic Gates: Realization in a Flow Device](#)

[19.4 Enzyme-Based Fredkin Gate Processing Biomolecular Signals Prior to the Bioelectronic Interface](#)

[19.5 Reversible DNA-Based Feynman Gate Activated by Signals Produced by the Enzyme-Based Fredkin Gate](#)

[19.6 Conclusions and Perspectives](#)

[19.A Appendix](#)

[References](#)

[20 Conclusions and Perspectives: Further Research Directions and Possible Applications](#)

[Index](#)

[End User License Agreement](#)

List of Tables

Chapter 2

[Table 2.1 The sequence of extraction operations for a given illustrative SAT ...](#)

Chapter 5

[Table 5.1 List of some common RNA aptamers with corresponding fluorogenic lig...](#)

Chapter 10

[Table 10.1 Principal characteristics of the three experimental systems capabl...](#)

Chapter 12

[Table 12.1 Truth table of various basic logic gates.](#)

[Table 12.2 General classification of different advanced DNA logic circuits.](#)

Chapter 14

[Table 14.1 Paths and values encoded by the different test tubes used for solv...](#)

Chapter 17

[Table 17.1 Comparison of conventional fluorescence and nanopore decoding meth...](#)

List of Illustrations

Chapter 1

[Figure 1.1 Moore's law - exponential increase of transistors on integrated c...](#)

[Figure 1.2 Biomolecular computing systems mimicking operation of different B...](#)

[Figure 1.3 The discoverers of the structure of DNA. James Watson \(b.1928\) at...](#)

[Figure 1.4 The structure of the DNA double helix. The atoms in the structure...](#)

[Figure 1.5 Leonard Adleman - a pioneer of the biomolecular computing; the ph...](#)

[Figure 1.6 The principle of Leonard Adleman's DNA computer to solve the "tra...](#)

[Figure 1.7 The DNA computer playing the tic-tac-toe game. Shown in the foreg...](#)

[Figure 1.8 Atomic force microscopy \(AFM\) images of DNA origami with differen...](#)

[Figure 1.9 An example of a DNA chip used in the DNA sensing and computing. T...](#)

[Figure 1.10 Logic program \(a\) and automatically generated chemical reaction ...](#)

[Figure 1.11 PCR method for copying DNA molecules: a thermal cycler, componen...](#)

[Figure 1.12 Apparatus operating as the end-to-end automatic DNA data storage...](#)

Chapter 2

[Figure 2.1 Adleman's DNA computing procedure \[2\]. For \(a\) given super graph,...](#)

[Figure 2.2 Lipton's graph \[3\] for constructing a binary number for a general...](#)

[Figure 2.3 Representation of surface-based DNA computing method \[4\].](#)

[Figure 2.4 Representation of surface-bound DNA sequence.](#)

[Figure 2.5 Illustration of four literal strings for the DNA hairpin formatio...](#)

[Figure 2.6 \(a\) The five-node graph and \(b\) its complementary graph used to s...](#)

[Figure 2.7 Chao's single-molecule DNA navigator \[13\] for solving the maze.](#)

[Figure 2.8 DNA origami is a group of linked dsDNA. The structure consists of...](#)

Chapter 3

[Figure 3.1 The simulation of a register machine. \(a\) Simulation of bounded r...](#)

[Figure 3.2 State graph with state transition implemented by CRNs.](#)

[Figure 3.3 Implementation of Rule 110 Automata. Two different arrangements ...](#)

[Figure 3.4 Diagrams of the DNA implementation models. \(a\) Mapping model of b...](#)

[Figure 3.5 The system performing encoding, computing, and decoding signals i...](#)

[Figure 3.6 \(a\) Sequence of reactions for the three-phase clock based on the ...](#)

[Figure 3.7 A folded eight-point four-parallel real-valued FFT processor.](#)

[Figure 3.8 Molecular reactions for each element of the FFT processor in Figu...](#)

Chapter 4

[Figure 4.1 Examples of deoxyribozyme-based logic gates. \(a\) One of the first...](#)

[Figure 4.2 AND deoxyribozyme ligase gate connected to YES RCDZ gates. \(a\) DN...](#)

[Figure 4.3 Design of strand displacement \(seesaw\) DNA logic gates \[53\]. \(a\) ...](#)

[Figure 4.4 DNA strand displacement logic gates attached to a DNA origami til...](#)

[Figure 4.5 Design of molecular beacon \(MB\)-based DNA logic gates. \(a\) MB pro...](#)

[Figure 4.6 4WJ DNA logic gates and tile-integrated DNA circuits. \(a\) 4WJ NOT...](#)

Chapter 5

[Figure 5.1 Nucleic acid nanostructure designing techniques. \(a\) DNA origami ...](#)

[Figure 5.2 \(a\) Examples of the diverse application of nucleic acid aptamers....](#)

[Figure 5.3 Common binary logic gate symbols and truth tables.](#)

[Figure 5.4 Logic gates design principle using MG-binding RNA aptamer. \(a\) Re...](#)

[Figure 5.5 Examples of combinatorial logic gates using half-adder and full-a...](#)

Chapter 6

[Figure 6.1 Representative tile-based DNA nanostructures. \(a\) 2D DNA crystall...](#)

[Figure 6.2 Representative DNA origami nanostructures. \(a\) DNA origami folded...](#)

[Figure 6.3 DNA/RNA nanotechnology-enabled toolbox for synthetic circuits. A ...](#)

[Figure 6.4 Typical AND gate circuits. \(a\) A DNzyme-enabled AND gate.. \(...](#)

[Figure 6.5 Scheme of an integrated live-cell circuit enabled by DNA/RNA nano...](#)

Chapter 7

[Figure 7.1 Engineering steps of DNA switches. \(I\). DNA can adopt a wide range...](#)

[Figure 7.2 \(a\) Cartoon representation of the population-shift mechanism. The...](#)

[Figure 7.3 Based on the population-shift model, different strategies exist t...](#)

[Figure 7.4 Creating switches based on the population-shift model for double ...](#)

[Figure 7.5 Exploiting allosteric effectors to create logic gates. \(a\) Using ...](#)

[Figure 7.6 Examples of logic gate created using the strategies discussed in ...](#)

[Figure 7.7 \(a\) Two or more switches with different affinities for the input ...](#)

Chapter 8

[Figure 8.1 The universal input/output mechanism of DNA-based logic circuit. ...](#)

[Figure 8.2 Schematic representation of the YES gate based on the hairpin str...](#)

[Figure 8.3 Schematic representation of the DNA computing assembly based on t...](#)

[Figure 8.4 Schematic representation of cascaded DNA computation based on the...](#)

[Figure 8.5 Schematic representation of the AND gate based on the strand disp...](#)

[Figure 8.6 Schematic representation of the parity generator/checker based on...](#)

[Figure 8.7 Schematic representation of the AND logic gate that consists of t...](#)

[Figure 8.8 Schematic representation of the three-input majority logic gate....](#)

[Figure 8.9 Schematic representation of the 2-to-4 DC.](#)

[Figure 8.10 The electronic diagram \(i\) and the schematic representation \(ii\)...](#)

[Figure 8.11 \(a\) Schematic representation of the label-free 8-to-3 encoder. \(...\)](#)

[Figure 8.12 \(i\) Schematic representation of DNA structural conversions induc...](#)

[Figure 8.13 Schematic representation of the logic operations based on **HP26**-t...](#)

[Figure 8.14 \(i\) Schematic representation of the DNA-MTC supramolecular logic...](#)

[Figure 8.15 Schematic representation of the reconfigurable DNA-supramolecula...](#)

Chapter 9

[Figure 9.1 Truth tables and symbols for the elementary two-input Boolean log...](#)

[Figure 9.2 Three-color QD logic gates. \(I\) Mechanism for control of hybridiz...](#)

[Figure 9.3 Time-gated photonic logic gates with LLCs as FRET donors. \(I\) ET-...](#)

[Figure 9.4 DNA-mediated AuNP aggregation as a colorimetric indicator. \(I\) Vi...](#)

[Figure 9.5 Three-input logic gate with an AuNP quencher. \(I\) Cooperative bin...](#)

[Figure 9.6 PAA-templated fluorescent AgNC logic gates. \(I\) Transfer of AgNC ...](#)

[Figure 9.7 Fluorescence quenching by graphene oxide for two-output logic cir...](#)

[Figure 9.8 Logic gate with CDs \(labeled as “C-dots”\) and EB. \(I\) Adsorption ...](#)

[Figure 9.9 Three-input logic circuit with a conjugated polymer FRET donor. \(...](#)

Chapter 10

[Figure 10.1 Principle of DNA strand displacement \(DSD\) reactions \(a,b\) and o...](#)

[Figure 10.2 Mechanism of the genelet reaction system \(a\) and network oscilla...](#)

[Figure 10.3 Mechanism of the PEN DNA toolbox reaction system \(a\) and network...](#)

[Figure 10.4 Reaction-diffusion edge detection pattern engineered with DNA st...](#)

[Figure 10.5 PEN autocatalyzers generate programmable concentration fronts th...](#)

[Figure 10.6 “Go-fetch” fronts \(a\) and waves and spirals with PEN reactions \(...](#)

[Figure 10.7 Strategies to control the diffusion and geometry of RD patterns....](#)

[Figure 10.8 Steady-state “colony” formation in a population of synergic part...](#)

[Figure 10.9 Illustration of Wolpert's concept of positional information as a...](#)

[Figure 10.10 Static pattern of positional information engineered with DNA st...](#)

[Figure 10.11 Static patterns of positional information can be engineered wit...](#)

Chapter 12

[Figure 12.1 \(a\) The operation of half-adder/half-subtractor based on the uni...](#)

[Figure 12.2 \(A\) The operation of encoder/decoder based on the universal GO/D...](#)

[Figure 12.3 \(a\) The parity checker for identifying even/odd numbers from nat...](#)

[Figure 12.4 \(a\) The five-digit DNA keypad lock based on silver microspheres ...](#)

[Figure 12.5 Concatenated DNA logic circuits with \(a\) visual.\(b\) fluoresc...](#)

[Figure 12.6 \(a\) Schematic illustration of the DNA “contrary logic pairs” lib...](#)

[Figure 12.7 The integration of DNA computing with \(A\) peptides. \(a\) Equivale...](#)

Chapter 13

[Figure 13.1 Toehold-mediated strand displacement reactions. \(a\) A DNA duplex...](#)

[Figure 13.2 Toehold switch riboregulators \[18\] and input logic \[20\]. \(a\) Toe...](#)

[Figure 13.3 Switching_guide RNAs using toehold-mediated strand displacement....](#)

[Figure 13.4 Activation of RNA interference via toehold-mediated strand displ...](#)

Chapter 14

[Figure 14.1 A prototypical DNA strand displacement reaction showing one of t...](#)

[Figure 14.2 Allosteric toehold mechanism. A first input invades the target d...](#)

[Figure 14.3 \(a\) Cooperative hybridization of the inputs induces the displace...](#)

[Figure 14.4 Associative toehold mechanism. The helper strand \(orange\) facili...](#)

[Figure 14.5 Remote toehold mechanism. A spacer separates the toehold and the...](#)

[Figure 14.6 The toehold exchange reaction. The process is fully reversible v...](#)

[Figure 14.7 Programmed reconfiguration of DNA assemblies using the strand di...](#)

[Figure 14.8 Programmed reconfiguration of DNA assemblies using the strand di...](#)

[Figure 14.9 Dynamic reconfiguration of DNA-based interlocked catenanes using...](#)

[Figure 14.10 Programmed motion of a bipedal DNA walker. An attaching strand ...](#)

[Figure 14.11 Autonomous directional motion of a DNA bipedal walking device. ...](#)

[Figure 14.12 A DNA-based transporter. \(a\) Details of the movement of the wal...](#)

[Figure 14.13 Directed graph G representing Adleman's Hamiltonian path proble...](#)

[Figure 14.14 Adleman's DNA solution to the Hamiltonian path problem.](#)

[Figure 14.15 Graphical representation of a 2-SAT problem.](#)

[Figure 14.16 The Boolean logic operators NOT \(a\), AND \(b\), and OR \(b\). The d...](#)

[Figure 14.17 \(a\) Deoxyribozyme-based AND logic gate design with hairpins pre...](#)

[Figure 14.18 Strand displacement cascade illustrating a toehold exchange str...](#)

[Figure 14.19 The DNA seesaw architecture. \(a\) Abstract seesaw gate formalism...](#)

[Figure 14.20 Operation of logic gates immobilized on a solid-phase support. ...](#)

[Figure 14.21 Early developments in DNA catalytic systems. \(a\) Kinetic contro...](#)

[Figure 14.22 Entropy-driven catalytic DNA system. The catalyst first interac...](#)

Chapter 15

[Figure 15.1 Basic molecular logic units and their activation during training...](#)

[Figure 15.2 The molecular assembly line and its operation. \(a\) The basic com...](#)

[Figure 15.3 Scheme of a walking DNzyme and its track. \(a\) The walking princ...](#)

[Figure 15.4 Domain-level \(a\) and schematic \(b\) representations of the miRNA-...](#)

[Figure 15.5 Mean squared displacement, \$\langle x^2\(t\) \rangle\$.](#)

[Figure 15.6 The irreversible catalysis of substrates to products leads to th...](#)

[Figure 15.7 \(a\) Implementation of a state transition through DNAzymes. \(b\) \$D_{0,s_1}\$](#)

Chapter 16

[Figure 16.1 Conjectured self-assembly of DNA origami. \(a\) Phase 1: Synthesis...](#)

[Figure 16.2 Simplistic illustration of primitives: a conceptual illustration...](#)

[Figure 16.3 Strand displacement reaction. \(a\) Before strand displacement. \(b...](#)

[Figure 16.4 Zip transformation. \(a\) Before zip. \(b\) After zip. Strands \$s_1, \dots\$](#)

[Figure 16.5 Unzip transformation. \(a\) Before unzip. \(b\) After unzip. Strands...](#)

[Figure 16.6 Zip and unzip by DNA hairpins. \(a\) A pair of adjacent hairpins. ...](#)

[Figure 16.7 Zip and unzip by strand-displacing polymerase. \(a\) Unhybridized ...](#)

[Figure 16.8 AFM characterization. \(a\) M1 before zip. \(b\) M1 after zip. \(c\) M...](#)

[Figure 16.9 Dynamic devices created from a single DNA origami. \(a\) Examples ...](#)

[Figure 16.10 Dynamic network of nanocontainers using DNA origami transformer...](#)

[Figure 16.11 Initiated transformations: repeated units of these consolidated...](#)

Chapter 17

[Figure 17.1 Conventional DNA computing and its decoding. \(A\) Adleman \[1\] des...](#)

[Figure 17.2 Applications of nanopore technology. \(a\) Schematic illustration ...](#)

[Figure 17.3 Nanopore decoder methodology. NAND operation in a droplet system...](#)

[Figure 17.4 DNA relay mechanism. \(a-f\). Conceptual diagrams of the DNA relay...](#)

[Figure 17.5 Nanopore decoder applications. \(a\). Four individual operations as...](#)

[Figure 17.6 Nanopore detection of miRNAs. \(a\). MiRNA detection using DNA prob...](#)

Chapter 18

[Figure 18.1 Pipeline of a typical DNA-based digital storage system.](#)

Chapter 19

[Figure 19.1 General scheme of the system operation: the enzyme computing sys...](#)

[Figure 19.2 Two enzyme systems used in this study and their corresponding lo...](#)

[Figure 19.3 \(a\) Potential measurements on the sensing electrode – general sc...](#)

[Figure 19.4 \(a\) Optical analysis of the DNA released \(note that the DNA was ...](#)

[Figure 19.5 The general scheme illustrating the DNA-based 3-AND logic gate o...](#)

[Figure 19.6 Principal scheme of a three-input deoxyribozyme AND gate. Strand...](#)

[Figure 19.7 Digital performance of the DNA logic gate. \(a\) General scheme. \(...\)](#)

[Figure 19.8 The truth table \(a\), block diagram \(b\), and equivalent electroni...](#)

[Figure 19.9 Experimental realization of the biocatalytic Fredkin gate in the...](#)

[Figure 19.10 Experimental realization of the Fredkin gate \(photo of the flow...](#)

[Figure 19.11 The block scheme of the entire system including \(A\) the enzyme-...](#)

[Figure 19.12 Operation of the electrochemical interface between the enzyme a...](#)

[Figure 19.13 \(A\) Logic scheme \(including the ID and XOR gates operating in ...](#)

[Figure 19.14 Schematic representation of the DNA reactions mimicking XOR fun...](#)

[Figure 19.15 \(a\) Nerve cells deposited on a microelectrode array. \(b\) Beyond...](#)

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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

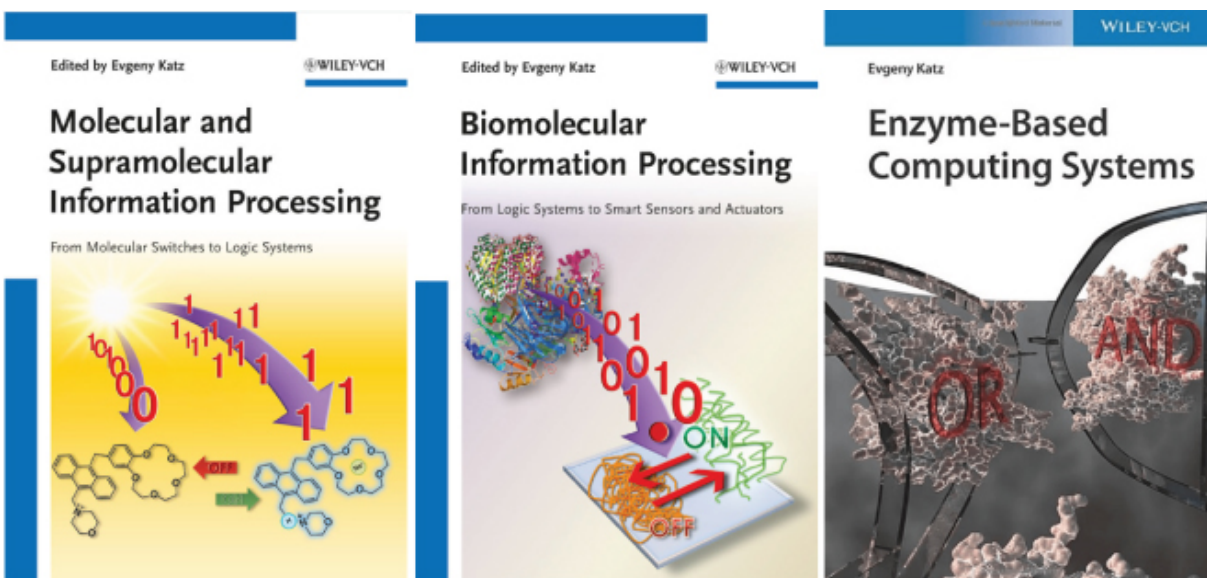
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1

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.

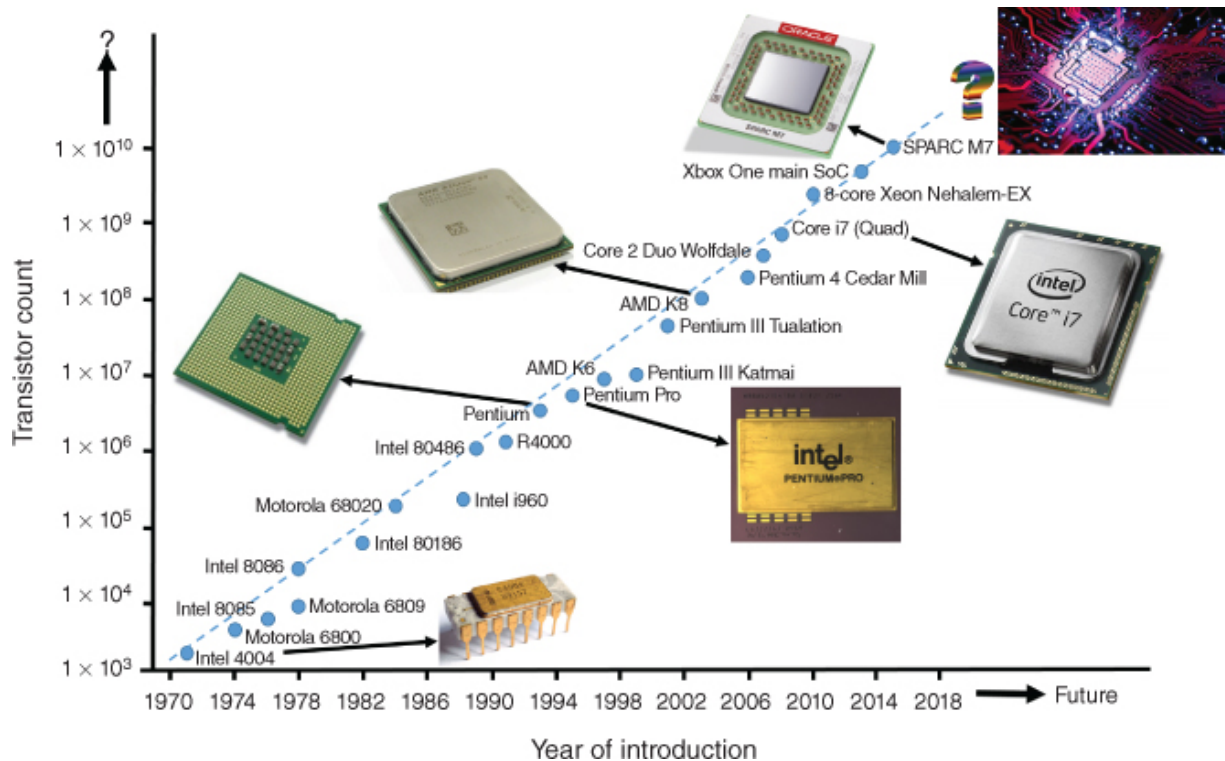


Figure 1.1 Moore's law – exponential increase of transistors on integrated circuit chips. (The plot shown in the figure is based on the data provided by Wikipedia: https://en.wikipedia.org/wiki/Moore%27s_law.)

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

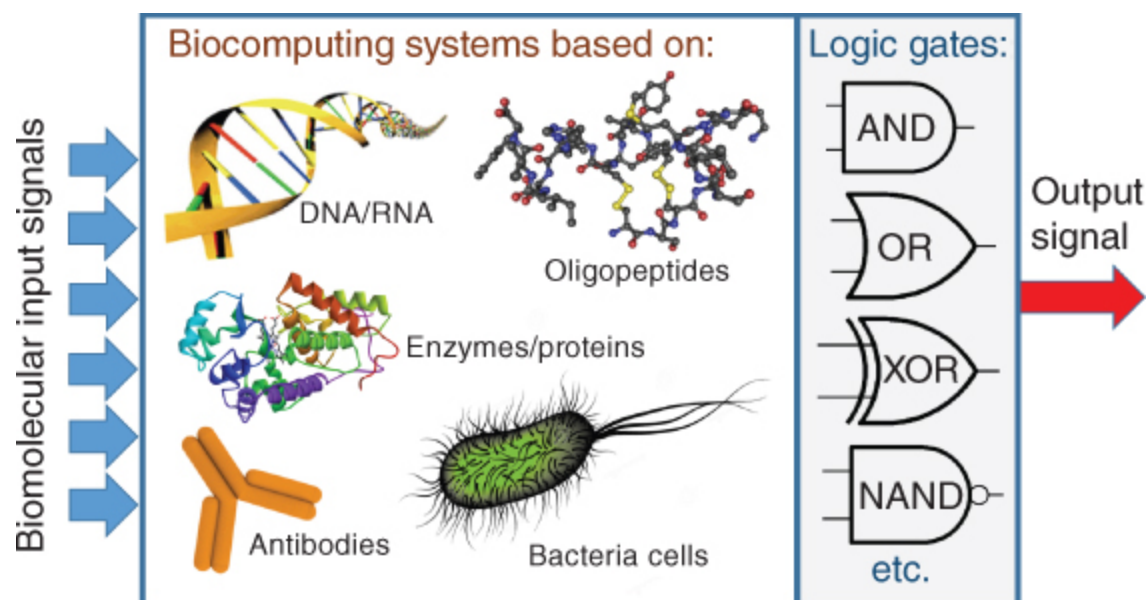


Figure 1.2 Biomolecular computing systems mimicking operation of different Boolean logic gates and circuitries can be based on various species including oligopeptides, enzymes/proteins, DNA/RNA, antibodies, and even whole biological (e.g., microbial) cells.

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