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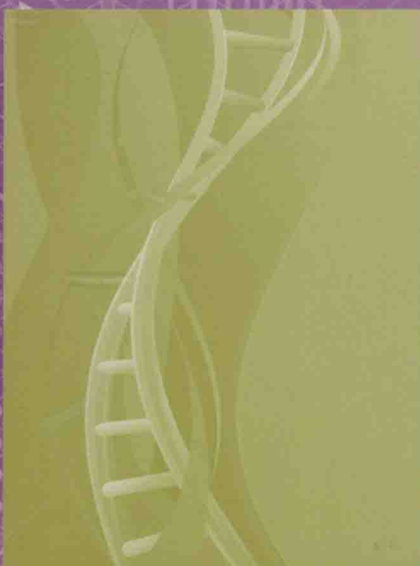

Introduction to DNA Self-Assembled Computer Design

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To Andrea and Ian
To Mitali, Niel, and Kiron

Acknowledgments

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Introduction

An Introduction to DNA Self-Assembled Computer Design describes how biological molecules and nanotechnology can impact the ways we design, build, and use computer systems. From macroscopic to molecular scales, self-assembly can be found creating the complex structures and functions that underpin our world. Self-assembly, however, is a process that receives little coverage in traditional engineering yet has impact on almost every engineered system. Biology is ripe with examples of complex self-assembly and these examples inspire us to approach the engineering of complex computer systems in new ways. Written for a general technical audience, this book is intended for readers who wish to learn what they need to understand this fast growing and ground breaking field.

Readers who may have forgotten some of their introductory biology and chemistry will find some help in Chapter 2, which is a survey of the self-assembly process that we build upon in later chapters. Readers who are unfamiliar with techniques for integrated circuit design will benefit from a solid review of microelectronics and VLSI design. To augment such a review we provide a brief description of conventional circuit fabrication techniques at the end of this chapter.

Device manufacturing at dimensions that approach tens of nanometers has significant challenges that stem from the finite size and structure of matter. In spite of such challenges, commercial microprocessor manufacturers continue to achieve ever smaller device feature sizes but at the cost of escalating manufacturing complexity. Thus, new methods for building computers that can reduce manufacturing costs and achieve performance equal to or greater than conventional systems will create new opportunities for computing. We will highlight some of these new opportunities and discuss how self-assembly can enable new modes of computation in Chapter 7. First, we begin our discussion of self-assembly by contrasting conventional top-down fabrication methods against the bottom-up techniques that will play a role in self-assembled computer fabrication.

1.1 Top-Down Versus Bottom-Up Fabrication

Top-down fabrication methods impose control over the placement, composition, and structure of materials from macroscopic bulk stock. Subtractive or additive processes, such as those employed in photolithography, are fundamentally top-down because structure is created by selectively depositing or removing bulk solids (or liquids) to form desired patterns. Imprint lithography is also a top-down process since it uses a macroscopic pattern (i.e., a stamp or master) to impress structure upon a uniform (bulk) surface. The common feature of top-down processes is a continuous reduction in the characteristic length scale of material structure from the macroscale to the molecular scale. For example, the imprint master must mechanically interface with the macroscopic stamp aligner and, by a smooth transition of size scales from the bulk stamp to the nanoscale pattern on the underside of the stam, come into commensurate contact with the target surface. For this process to be useful, the features of the stamp must convey nanoscale structural properties to the surface with high fidelity (e.g., the target surface must take on the same pitch, aspect ratio, etc. as the features on the stamp pattern.) The inherent challenge with top-down fabrication is that as feature sizes approach molecular scales (i.e., 0.1 to 10 nm) materials no longer behave in the same rational and deterministic fashion that we encounter at macroscopic dimensions. Thus, a smooth transition from the macroscale to the molecular scale will require innovation to maintain the traditional device scaling (e.g., from 45 to 32 nm) that has driven the computer manufacturing industry.

The alternative to top-down fabrication is bottom-up fabrication whereby structure is created by the assembly of precursors (or blocks) that grow outward from a nucleation site. The everyday variety of bottom-up fabrication uses precursors built from top-down methods. For example, the stones in a stone wall are laid in place such that the wall grows outward from its foundation. Contrast this method with a top-down method where a wooden form is built to define the wall. In fact, form-built structures rely on both top-down fabrication (e.g., the form) and bottom-up fabrication through the molecular adhesion of the fill material (e.g., concrete). Unlike top-down fabrication, bottom-up processes typically rely on local interactions between precursors (and their environment) alone to create large-scale structure.

Self-assembly is a mechanism for bottom-up fabrication in which the precursors are only weakly controlled by external environmental parameters such as temperature or reaction time. A comprehensive survey of bottom-up self-assembly is beyond the scope of this introduction but can be found in any good text on chemical synthesis. Fundamentally, thermodynamics governs