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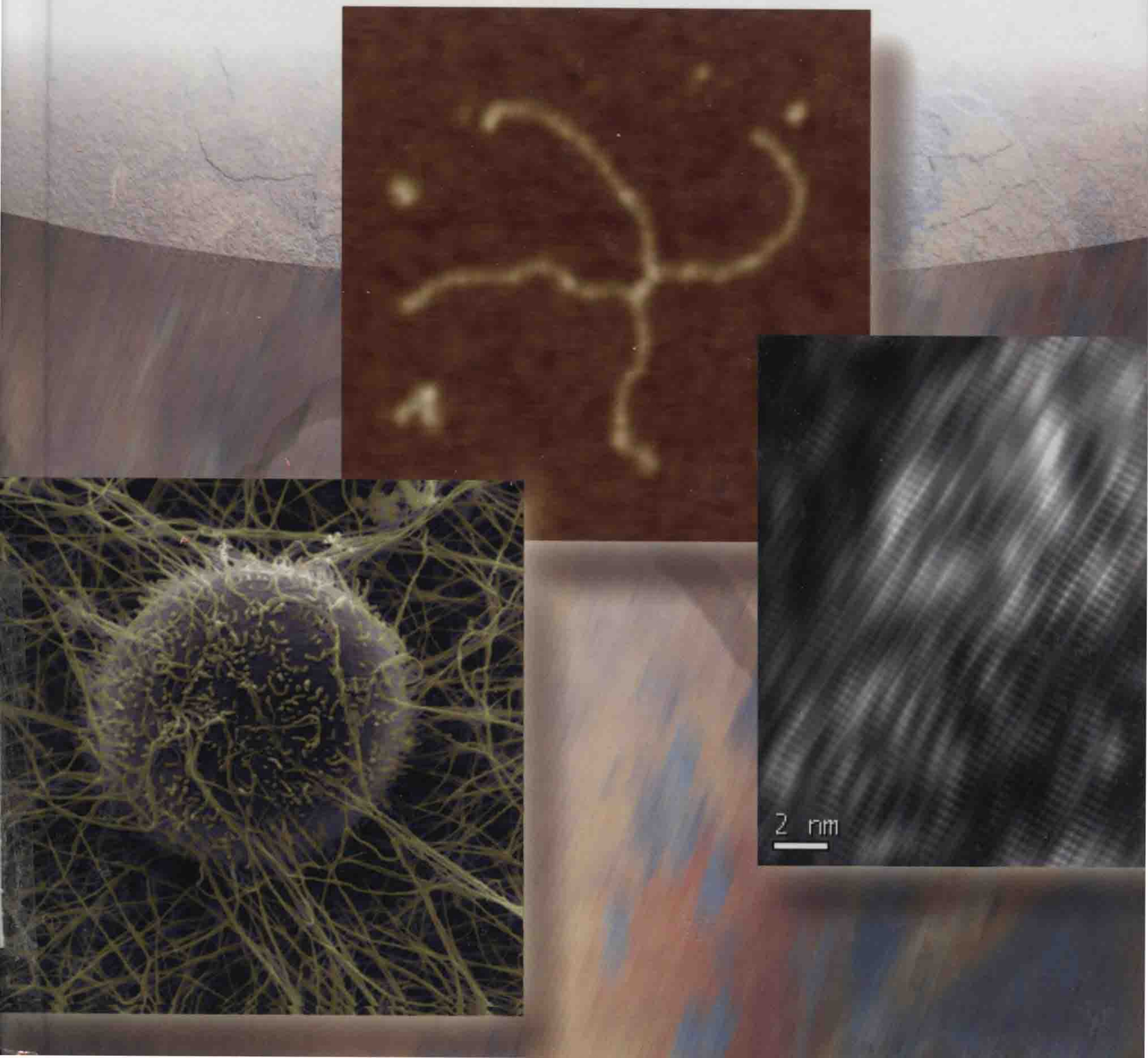
Designing materials inspired by nature



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Designing Materials Inspired by Nature

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Left: Atomic force microscopy image of a self-assembled artificial 4-arm DNA junction; image size: 350 nanometer × 350 nanometer. (Courtesy of Alexander Huhle, Ralf Seidel, and Michael Mertig, Technische Universität Dresden.)

Middle: Human hematopoietic stem cell growing in a fibrillar network of collagen Type I on a silicone substrate with a reactive polymer coating. (Courtesy of Ina Kurth, Leibniz Institute of Polymer Research Dresden e.V., Germany.)

Right: High-resolution TEM image of a trabecula of rat bone showing a mineralized collagen bundle (below left to above right), about 15nm across, composed of triple helical collagen fibrils, about 1.5nm across. The fine striation pattern corresponds to the lattice constant of the *c*-axis of hydroxyapatite, 3.44 Å. The pattern of large stripes running parallel to the fibril axis corresponds to the *a*-lattice planes. (See also D. Grüner, T. Kollmann, C. Heiss, R. Schnettler, R. Kniep, P. Simon, "Hierarchical structure of spongeous tibia head of rats: SEM studies and HR-TEM of FIB prepared trabecula", to be published. (Courtesy of Paul Simon, Max Planck Institute for Chemical Physics of Solids Dresden, Germany.)

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Preface

The various challenges that we are confronted with today require novel solutions that will influence future developments in the field of materials science worldwide. This concerns the necessity to master the transition to regenerative energies. Also, the foreseeable exhaustion of essential resources necessitates developing new materials strategies, such as to use renewable raw materials, to exploit low-grade ores, or to establish widespread materials recycling. In view of this situation, the attitude toward nature has changed: in the past, the progress of mankind was based on extending its domination over nature. Now consensus is growing that future progress has to be achieved in close accordance with nature. Such attitude gave rise to the concept of biologically inspired materials engineering. It includes the development and production of novel materials, such as living tissue for regenerative bone therapy, and novel materials processing techniques, such as biologically controlled mineralization via microorganism–silica hybrid composites. "Bio-inspired" relates to inspiration by some mechanisms or processes present in the organic world, and the attempt to adapt them to technology. According to this nomenclature, "bio-inspired approach" denotes the following: The richness of biomolecular structures and processes serves as basis for the creation of nano-structured materials with novel functionalities, commonly summarized under the term "bionanotechnology." Here we follow the definition of bionanotechnology as proposed by Ehud Gazit in his book "Plenty of Room for Biology at the Bottom: An Introduction to Bionanotechnology" (Gazit, 2007). In the following, we will focus on materials or processes where adaptation includes the use of biomolecules or living cells, and hence on biologically inspired materials development in a narrower sense. The enormous progress in molecular biology and microbiology over the past 50 years has generated a huge knowledge as the basis to tackle such tasks. Genetic engineering allows the generation of tailored recombinant proteins or microorganisms and thus provides a large "toolbox" for the implementation of biological structures in a technical environment.

Progress of synthetic biology will probably provide a further qualitative leap. In the paper entitled "Creation of a bacterial cell controlled by a chemically synthesized genome," J. Craig Venter and coworkers reported the creation of an artificial bacterial chromosome and its successful transfer into a bacterium, where it replaced the native DNA (Gibson *et al.*, 2010). Under the control of the synthetic genome, the cell started to produce proteins, eventually leading to DNA replication and cell division. The creation of this self-replicating synthetic bacterial cell called *Mycoplasma mycoides* JCVI-syn1.0 can be regarded as a milestone on the way from molecular genetics to synthetic biology. An old dream of biologists may become reality soon: engineering organisms designed for specific technological use, such as the efficient production of particular medical drugs or of biofuels via photosynthesis. Close interdisciplinary cooperation of biologists, materials scientists, chemists, physicists, and computer scientists is required to develop this research area successfully and to further public acceptance of the novel products, possibly including even artificial organisms in the future. Interdisciplinary approaches are also necessary regarding ethics and biosafety problems that require thorough assessments of the risk potential on the basis of profound and broadly oriented scientific work.

Based on our experience to teach biologically inspired materials science in various courses at the Technische Universität Dresden, our book aims at providing the basics of this scientific field for students of biology, biotechnology, bioengineering, materials science, chemistry, and physics and thus to lay the ground for interdisciplinary research. The already existing knowledge basis in bio-inspired materials science allows us to arrange practical results around a few general principles identified in the living world. Thus, we have organized the book in seven main chapters coauthored by two or three colleagues: Chapter 1 "Molecular units" by M. Mertig, W. Pompe, and G. Rödel; Chapter 2 "Molecular recognition" by W. Pompe and G. Rödel; Chapter 3 "Cell adhesion" by T. Pompe and W. Pompe; Chapter 4 "Whole-cell sensors" by W. Pompe and G. Rödel; Chapter 5 "Biohybrid silica-based materials" by W. Pompe, H.-J. Weiss, and H. Worch; Chapter 6 "Biomineralization" by M. Gelinsky, W. Pompe, and H.-J. Weiss; and Chapter 7 "Self-assembly" by M. Mertig and W. Pompe. It is recommended that one should begin with more biologically oriented subjects and later turn to those with a stronger materials science focus. The selection and the explanation of general principles have been motivated by particular biological case studies. Every chapter devoted to one such principle is introduced by a few subjectively selected biological case studies. These examples provide the background for elucidating the particular principle in the second section. In the third part of every chapter, examples for materials processing in engineering, medicine, and environmental technologies are given. We are aware that the subject of every chapter could be extended into a whole monograph. However, we see that students of materials science as well as of biology prefer to get an introduction to the whole field allowing them to initiate deeper studies of special topics. Therefore, we try to develop the basic principles as a kind of focusing and connecting part. In addition to biological principles, basic physical and chemical laws have been included since they are likewise essential for successful bio-inspired materials processing. Preferably, we chose a heuristic approach to the various topics. Occasionally, small tasks for quantitative estimates or simple modeling are formulated, including hints for the solutions. We hope that it will motivate the reader to address more complex calculations in the related original literature.

Acknowledgments

The engagement with bio-inspired materials science at the Technische Universität Dresden dates back to an elucidating and exciting discussion between one of us (WP) and Arthur Heuer of Case Western Reserve University at Cleveland 20 years ago. Just at that time, Arthur Heuer, together with a group of other well-known American materials scientists, issued a *Science* paper on "Innovative materials processing strategies: a biomimetic approach" (Heuer *et al.*, 1992), where he emphasized the great potential of mimicking biological processing strategies. He generously shared his ideas on what could possibly be done by materials scientists in this interdisciplinary research field. Later on, we repeatedly benefited from his personal engagement, as well as from that of Manfred Rühle at the Max-Planck Institute for Materials Science, Stuttgart, by establishing a research group for bio-inspired materials science at the Max-Bergmann Centre at the Technische Universität Dresden. We thank Arthur Heuer deeply for his great visionary advice and permanent support. We would also like to thank the many students and colleagues who supported us with valuable contributions of their research work and by reading drafts of particular chapters. Special thanks go to Michael Ansorge, Annegret Benke, Anne Bernhardt, Anja Blüher, Manfred Bobeth, Martin Bönsch, Horst Böttcher, Lucio Colombi Ciacchi, Florian Despang, Hermann Ehrlich, Angela Eubisch, Christiane Erler, Annett Groß, Katrin Günther, Thomas Hanke, Sascha Heinemann, Klaus Kühn, Mathias Lakatos, Lynne Macaskie, Sabine Matys, Iryna Mikheenko, Martin and Msau Mkandawire, Kai Ostermann, Ralf Seidel, Paul Simon, and Ulrich Soltmann, as well as to many colleagues for providing figures from their work. We also thank the staff of Wiley-VCH, in particular Ulrike Fuchs and Nina Stadthaus, whose engaged work and manifold advices during the extended preparation of the manuscript enabled us to finally complete it.

Dresden, Germany
March 2012

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Contents

1
Molecular Units

1.1
Case Studies

Living beings are "open" systems whose sustained existence requires fluxes. Since even very simple open systems such as a candle flame or a water jet form their own shape and restore it after a disturbance, one may readily accept the idea that more complex open systems are able to form and sustain more complex structures in space and time. Apparently, there are open systems involving chemical reactions with a tendency toward the formation of substances and reaction cycles with increasing complexity, ending up in the formation of life. The molecular processes of life are usually confined to enclosed (but not closed) spaces, the cells and their internal compartments. Eukaryotic cells, which are discriminated from prokaryotic cells by the presence of a nucleus harboring the vast majority of genetic information, are equipped with a variety of such functionally defined compartments, collectively summarized as organelles (Figure 1.1). This type of confinement is realized by membranes shielding the interior and controlling the flow of substances, energy, and information in and out. The information flow is facilitated by the membranes' capability of signal detection and transduction. Structural flexibility of the plasma membrane is a necessary precondition for cell motility and division. The cell is filled with cytoplasm, an assembly of functional entities and filamentous networks immersed in an aqueous solution, the cytosol.

Since there are good reasons for the assumption that all organisms have descended from a hypothetical common progenitor, their relationship has the topology of a tree and hence is usually visualized as a graph known as the phylogenetic tree of life (Figure 1.2). One can be sure that the tree of life obtained with a particular advanced technique, as the one in Figure 1.2, does not much differ from the real one and thus can serve as a basis for considerations as if it were the real one. As seen in the figure, the tree of life consists of three major domains. The vast majority of organisms are unicellular. Multicellular species are only found in a few branches of the Eukaryota, which are distinguished by the presence of a nucleus containing most of the genetic information. Autotrophic and heterotrophic organisms are present in every major domain. These terms refer to the source of the energy-rich organic substances (nutrients) required to drive the metabolism.

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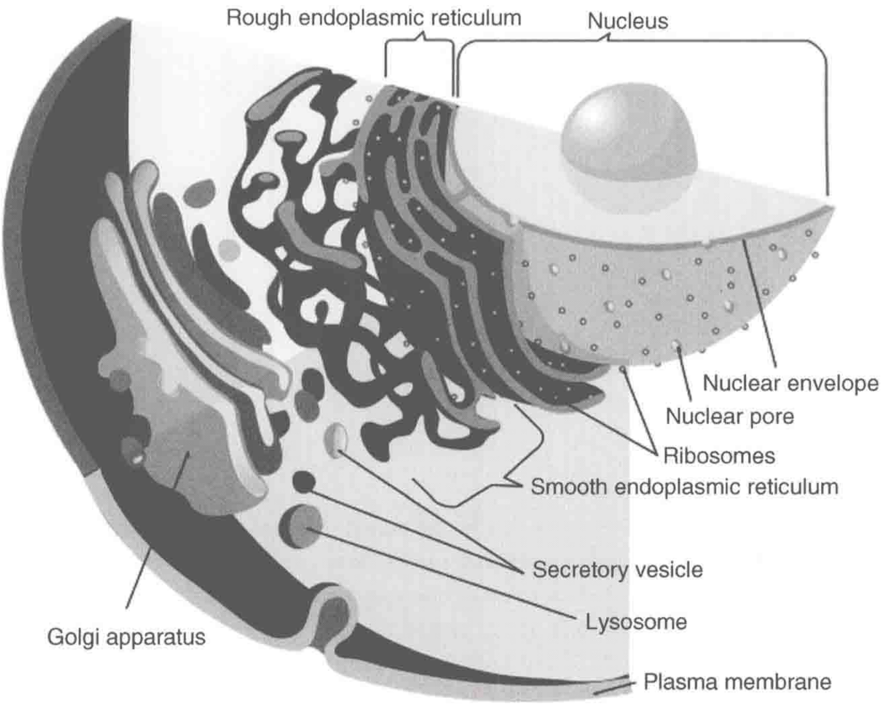

Figure 1.1 Eukaryotic cell structure with the endomembrane system. (*Source*: Wikimedia Commons; author Mariana Ruiz.)

Autotrophic organisms are able to produce the nutrients by themselves, starting from inorganic substances. In contrast, heterotrophic organisms are unable to synthesize their nutrients and hence have to acquire them by consuming organic substances. Besides the well-known photoautotrophy of plants, an alternative form of autotrophy, the so-called chemoautotrophy, is widespread among the Prokaryota. In the presence of oxygen, chemoautotrophic organisms make use of the energy released by oxidation, notably of inorganic substances, enabling them to live in extreme habitats such as salt lakes, hot springs, deep sea floors, and so on. This property makes chemoautotrophs interesting for bioengineering. Photoautotrophic cyanobacteria have recently been considered with respect to their suitability for biofuel production. Eukaryotes are especially valuable for biotechnology, bio-inspired materials development, and medical engineering. Fermentation by means of yeast, for example, has been applied for millennia. Recently, animal stem cells have been widely used in tissue engineering developments. The huge variety of organisms offers a wealth of objects with structures differing on the molecular level that may be suitable as building blocks in biotechnology and biologically inspired materials science. Today, we are still in a very early stage of exploring their potential. Our responsibility for the protection of life on Earth implies that progress in this field of research should always be complemented with adequate risk assessment.

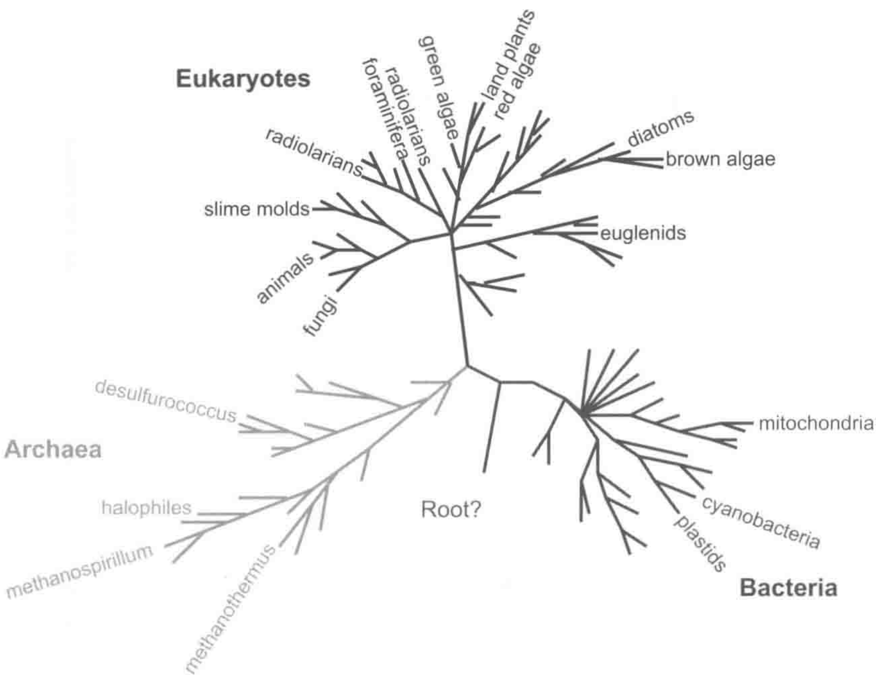

Figure 1.2 The phylogenetic tree of life based on the comparison of ribosomal RNA. (Bacteria and Archaea are also called Prokaryota. The names of most taxa are omitted here for simplicity.)

The sizes of the bimolecular structures investigated as potential building blocks range from molecular (0.2 nm) to cell size (0.1 mm) (Figure 1.3). Remarkably, organisms utilize only a small fraction of the chemical elements. Obviously, they are sufficient to form the large variety of organic compounds required for sustaining the processes of life. Let us consider the composition of the bacterium

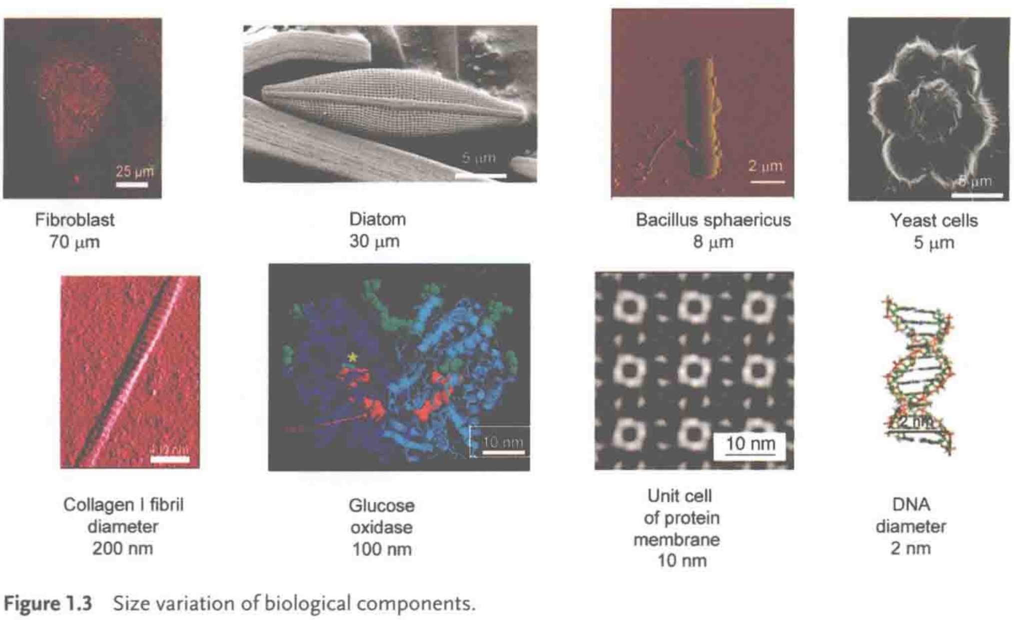

Figure 1.3 Size variation of biological components.

Table 1.1 Molecular composition of *E. coli* according to Nelson and Cox (2008).

	Percentage of total cellular weight	Approximate number of different molecular species
Water	70	1
Proteins	15	3000
Nucleic acids		
DNA	1	1–4
RNA	6	>3000
Polysaccharides	3	10
Lipids	2	20
Monomeric subunits and intermediates	2	500
Inorganic ions	1	20

Escherichia coli, with size is about 2 μm × 1 μm (Table 1.1). Its cytoplasm contains the nucleoid usually with one DNA chain, eventually a few small circular DNA molecules called plasmids, about 15 000 ribosomes (the sites of protein synthesis), 10 to several hundred copies of about 1000 different enzymes, about 1000 smaller organic compounds with a molecular weight less than 1000 (metabolites or coenzymes), and various inorganic ions. The cytoplasm is surrounded by the cell envelope, which consists of an outer and an inner membrane composed of lipid bilayers and peptidoglycans. Connected to the envelope are specific protein structures such as flagellae for cell propelling, pili providing adhesion sites, and surface layer proteins for mechanical stabilization and acting as filter and ion transport structures.

Eukaryotic cells with a size of about 5–100 μm show a higher structural complexity. The essential differences to bacteria are the presence of a nucleus, a number of membrane-enclosed organelles (e.g., mitochondria, endoplasmic reticulum, Golgi complexes, peroxisomes, and lysosomes), and the cytoskeleton, a highly structured network of protein filaments (microtubules, actin filaments, and intermediate filaments) organized by numerous proteins that regulate the assembling and disassembling of the various filaments. Characteristic components of plant cells are chloroplasts and vacuoles. A concise overview of the structure and properties of the main groups of biomolecules available for a bottom-up design of nanostructured materials – nucleic acids, proteins, carbohydrates, and lipids – is provided below.

1.1.1
Nucleic Acids

The storage, replication, and transfer of genetic information in living organisms is mediated by chain-like macromolecules called nucleic acids, the deoxyribonucleic acid (DNA) and several types of ribonucleic acid (RNA) (Figure 1.4).