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Bharat Bhushan

Biomimetics

Bioinspired Hierarchical-Structured Surfaces for Green Science and Technology

Third Edition

Springer

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To my grandkids Sahana, Ashwin,
Joya and Nivaan.








Foreword

Our planet has a unique biological diversity of about 1.8 million different species of living organisms that have been scientifically documented. The overwhelming diversity of plants and animals in shape, color, and function has fascinated students and scientists. What is more, it is estimated that the real number of species is much higher: on the order of 10 million species.

Each of these approximately 10 million species has optimized "technical" solutions to particular environmental conditions. The results of millions of years of biological evolution of millions of species are freely available to scientists that begin looking to nature's solutions for ideas. The most exciting solutions happen on surfaces, the boundary layer, and interface between solids and their gaseous or liquid environment. Surfaces define the boundaries for the well-structured world of solids, and it is surfaces that define their interactions.

Concise and systematic research in biology and technical innovations started only in the 1970s. "Bionics," "biomimicry," and "biomimetics" are terms used for this field. Until the 1980s, bionics concentrated on mechanical functions like robotics and airplane development. Surfaces did not really play a role—despite the fact that surfaces are an essential part of all solids.

In 1977, when I discovered the functions of biological hierarchical structuring and the self-cleaning abilities of certain plant surfaces like lotus leaves, I published the results in German in a purely academic journal—exotic for an engineering audience. Nobody took any notice. Then, it was difficult for scientists to talk across disciplines: different languages and seemingly different aims. Today, the cross-disciplinary field of biomimetics has changed this situation dramatically for the better: Engineers listen to biologists—and biologists are aware of technical potentials in their research and discuss them with materials scientists.

There is one outstanding scientist who has reinforced this process: Prof. Bharat Bhushan. Bharat, a materials engineer/physicist by education and practice and not a botanist, became interested in biomimetics in the 1990s. He recognized the enormous importance of biomimetic materials and their surfaces for technical applications. When the first edition of his "Biomimetics—Bioinspired Hierarchical-Structured Surfaces for Green Science and Technology" appeared in 2012, it was an

inspiration to scientists; for students, this was the first time a comprehensive textbook was available. Since then, he extensively revised the book in 2016 and now has prepared the expanded third edition in 2018. This third edition follows the revised fourth edition of his companion monumental Springer Handbook of Nanotechnology in 2017.

The amended third edition recapitulates and expands on the first two editions to provide a comprehensive review of the field. It covers not only topics such as lotus leaves, rose petals, and salvinia leaves, but is pushing boundaries looking at low drag and antifouling properties of shark skin, skimmer bird, rice leaves, and butterfly wings. The book covers broad biomimetic topics from solid explanations of superphobic/superphilic, self-cleaning, and antifouling surfaces (lotus, rose petal, salvinia, rice leaf, and butterfly wings) to more discrete topics including structural coloration (butterfly wings), mechanical toughness and durability (nacre), reversible adhesion (gecko feet), water harvesting and purification, fluid slip, insects locomotion, piercing and stinging, and self-healing materials. The book even ventures beyond the sciences to discuss the influence of biomimetics on art and architecture. As a biologist, I congratulate him and I am convinced it will be a great success and an important resource for all scholars of biomimetics.

Bonn, Germany

Dr. Wilhelm Barthlott
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and Former Director of the Nees Institute
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and Foreign Member of the Linnean Society London

Preface to the Third Edition

Biomimetics is derived from the Greek word biomimesis. It means **mimicking biology or living nature, or living organisms**, and is also called biomimicry. Biologically inspired research allows derivation of optimal designs benefitting from improvements made during the evolution of living nature and efficient use of natural resources in a more sustainable and environmentally friendly (green) manner. Biological materials are highly organized from the molecular to the nano-, micro-, and macroscales, often in a hierarchical manner with intricate nanoarchitecture that ultimately makes up a myriad of different functional elements. The field of biomimetics or bioinspired hierarchically structured surfaces started to take off in the early 2000s with major developments in nanoscience and nanotechnology. The latter made it possible to create natural surfaces with features ranging from the molecular scale to the macroscale. The bioinspired materials and surfaces can be eco-friendly and are used for various commercial applications. They have generated significant interest and are helping to shape, what we call "green science and technology," a term used for the first time in the first edition of this book in 2012. The interest in green science and technology has also provided the impetus for the advancement. The field is highly interdisciplinary, spanning from biology, physics, chemistry, materials science, and engineering. As of 2018, the field contains only a handful of visionaries and leaders. This author is fortunate to be one of the early explorers.

Since the early 2000s, there have been significant advances in research, and many ideas are commercialized. With a continued understanding of the mechanisms relevant to species of living nature and the development of new materials and nanofabrication techniques, rapid advancements are expected in the next decade and beyond. It is expected that new inventions will play a major role in human life.

The first edition of the book was published in 2012, followed by an updated second edition in 2016. Given rapid advancements in the author's laboratory, there was a need to develop a third edition which is significantly expanded. This book provides a state of the art of the biomimetics field primarily related to interface science. The book starts with a fundamental understanding of how various living species provide the functionality, followed by modeling to develop optimum

structures and then fabrication of optimum structures using smart materials and fabrication techniques to provide the functionality of commercial interest. The book contains overviews of a large number of living species and examples of various structures fabricated in the laboratory.

The book should serve as an excellent text for a one-semester course in biomimetics/bioinspiration. The book can also serve as a textbook for an applied nanotechnology course. The book is also intended for use by novices as well as experts in the field, practitioners, solution seekers, and the curious. Applications should help in the advancement of the field.

The book is based on the work of outstanding contributions by past and present collaborators. These include:

Past and present students:

Zach Burton, Yong Chae Jung, James Hunt, Robert A. Sayer, Eun Kyu Her (Seoul National University, Korea); Brian Dean, Daniel Ebert, Gregory D. Bixler, Yunlu Pan, and Dalei Jing (Harbin Institute of Technology, China); Srimala Perara (University of Moratuwa, Sri Lanka); Andrew Theiss and Shan Peng (Wuhan University of Science and Technology, China); Samuel Martin, Wenjing Ma, and Dev Gurera.

Past and present postdoctoral fellows and visitors:

Dr. Michael Nosonovsky (University of Wisconsin, Milwaukee), Dr. Andrei G. Peressadko (Russia), Dr. Tae-Wan Kim (Pukyong National University, Korea), Prof. Kerstin Koch (University of Bonn, Germany), Dr. Manuel L. B. Palacio (Western Digital Corp., San Jose, California), Dr. Hyungoo Lee, Dr. P. K. Muthiah, Dr. Yongxin Wang, Dr. Philip S. Brown, and Dr. Joseph C. Cremaldi.

External Collaborators:

Prof. Wilhelm Barthlott (University of Bonn, Germany), Prof. Kerstin Koch (Rhine-Waal University of Applied Science, Kleve, Germany, Dr. Eui-Sung Yoon (KIST, Korea), Dr. Patrick Hoffman (EPFL, Lausanne, Switzerland), Dr. Andre Meister (CSEM, Switzerland), Prof. Scott. C. Schricker (Ohio State University, Columbus, Ohio), Prof. Joao F. Mano (University of Minho, Guimaraes, Portugal), Prof. Jiyu Sun (Jilin University, China), Prof. Shunsuke Nishimoto (Okayama University, Japan), Prof. Stanislav N. Gorb (University of Kiel, Germany), Prof. Eduard Arzt (Max Planck Institute for Metals Research, Stuttgart, Germany), and Prof. Stephen C. Lee (Ohio State University, Columbus, Ohio).

Their contributions are gratefully acknowledged. The author would also like to thank Joanne Holland for assistance in the preparation of the manuscript. Finally, the author would like to thank his wife Sudha for her constant support and encouragement.

Columbus, USA Bharat Bhushan

Preface to the First Edition

Nature has developed materials, objects, and processes that function from the macroscale to the nanoscale. The emerging field of biomimetics allows one to mimic biology or nature to develop nanomaterials, nanodevices, and processes which provide desirable properties. Hierarchical structures with dimensions of features ranging from the macroscale to the nanoscale are extremely common in nature to provide properties of interest. The biologically inspired materials and structured surfaces are eco-friendly or green with minimum human impact on the environment and are being explored for various commercial applications. This recognition has led to "green science and technology," the term used for the first time in this book.

There are a large number of objects including bacteria, plants, land and aquatic animals, and seashells with properties of commercial interest. The book presents an overview of the general field of biomimetics and biologically inspired surfaces. It deals with various examples of biomimetics, which include surfaces with roughness-induced superliquiphilic/superliquiphobicity, self-cleaning, antifouling, and controlled adhesion. It primarily focuses on the lotus effect which exhibits superhydrophobicity, self-cleaning, antifouling, low adhesion, and drag reduction. The book also includes the floating water fern which floats over water, rose petal effect which can provide either low adhesion or high adhesion, oleophobic/oleophilic surfaces inspired from aquatic animals, shark skin which exhibits low drag and antifouling, and gecko feet which exhibits reversible adhesion.

The book provides the theoretical background, characterization of natural objects and relevant mechanisms and inspired structured surface of commercial interest. We hope the book would serve as a catalyst for further innovations as well as serve as a useful reference to the emerging field of biomimetics. The book should also serve as an excellent text for a one-semester graduate course in biomimetics or as a companion text for a general course in nanotechnology. Given the interdisciplinary nature of the discipline, the appeal of the book is expected to be broad.

The work reported in the book is largely based on the pioneering contributions made by former and present students, postdoctoral fellows, and visiting scholars. Special mention is deserved by Dr. Yong Chae Jung, a former Ph.D. student

working in fabrication and characterization; Prof. Michael Nosonovsky, a former visiting scholar and an ongoing collaborator in the theoretical modeling; and Prof. Kerstin Koch of Nees Institute for Biodiversity of Plants at University of Bonn, Germany, who spent a sabbatical year in the author's laboratory. All of them contributed immensely to the research on the lotus effect. Dr. Tae-Wan Kim, a visiting scholar, contributed immensely on the theoretical modeling of gecko adhesion. Brian Dean, a graduate student, contributed to the understanding of the mechanisms of the shark skin effect. Other postdoctoral fellows and students who have contributed include Dr. Andrei G. Peressadko (gecko adhesion), Zack Burton (lotus effect), Eun Kyu Her (rose petal effect), Robert Sayer (gecko adhesion), James Hunt (salvinia effect), Daniel Ebert (lotus effect), and Dr. Hyungoo Lee (gecko adhesion). Finally, the author would like to thank Caterina Runyon-Spears for administrative support.

My special thanks go to my wife Sudha, who has been forbearing of my 24/7 commitment to science.

November 2011 Bharat Bhushan

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About the Author

Dr. Bharat Bhushan received an M.S. in mechanical engineering from the Massachusetts Institute of Technology in 1971, an M.S. in mechanics and a Ph.D. in mechanical engineering from the University of Colorado Boulder in 1973 and 1976, respectively, an M.B.A. from Rensselaer Polytechnic Institute at Troy, NY, in 1980, Doctor Technicae from the University of Trondheim at Trondheim, Norway, in 1990, a Doctor of Technical Sciences from the Warsaw University of Technology at Warsaw, Poland, in 1996, and Doctor Honoris Causa from the National Academy of Sciences at Gomel, Belarus, in 2000 and University of Kragujevac, Serbia, in 2011. He is a registered professional engineer. He is presently an Ohio Eminent Scholar and The Howard D. Winbigler Professor in the College of Engineering, the Director of the Nanoprobe Laboratory for Bio- & Nanotechnology and Biomimetics (NLB^2), and Affiliated Faculty in John Glenn College of Public Affairs at the Ohio State University, Columbus, Ohio. In 2013–2014, he served as an ASME/AAAS Science & Technology Policy Fellow, House Committee on Science, Space & Technology, United States Congress, Washington, D.C. His research interests include fundamental studies with a focus on scanning probe techniques in the interdisciplinary areas of biotribology/nanotribology, biomechanics/nanomechan ics, and biomaterials/nanomaterials characterization and applications to biotechnology/nanotechnology and bio mimetics. He is an internationally recognized expert of biotribology/nanotribology and biomechanics/nanomech anics using scanning probe microscopy and biomimetics. He is considered by some a pioneer of the tribology and

mechanics of magnetic storage devices. He is one of the most prolific authors. He has authored 8 scientific books, 90+ handbook chapters, 800+ scientific papers (One of Google Scholar's 1612 highly cited researchers (h > 100) and h-index—115+ with 65k+ citations; Web of Science h-index—90+; Scopus h-index—95+; ISI highly cited researcher in materials science since 2007 and in biology and biochemistry, 2013; ISI top 5% cited authors for journals in chemistry, 2011), and 60+ technical reports. He has also edited 50+ books and holds more than 25 US and foreign patents. He is Co-editor of Springer NanoScience and Technology Series, Co-editor of Microsystem Technologies, and Member of Editorial Board of PNAS. He has given more than 400 invited presentations on six continents and more than 200 keynote/plenary addresses at major international conferences. He is an accomplished organizer. He organized the Ist Symposium on Tribology and Mechanics of Magnetic Storage Systems in 1984 and the Ist Int. Symposium on Advances in Information Storage Systems in 1990, both of which are now held annually. He organized two international NATO institutes in Europe. He is the Founder of an ASME Information Storage and Processing Systems Division founded in 1993 and served as the founding chair during 1993–1998. His biography has been listed in over two dozen Who's Who books including Who's Who in the World. He has received more than two dozen awards for his contributions to science and technology from professional societies, industry, and US government agencies including Life Achievement Tribology Award and Institution of Chemical Engineers (UK) Global Award. His research was listed as the top ten science stories of 2015. He is also the recipient of various international fellowships including the Alexander von Humboldt Research Prize for Senior Scientists, Max Planck Foundation Research Award for Outstanding Foreign Scientists, and Fulbright Senior Scholar Award. He is a Foreign Member of the International Academy of Engineering, Russia, Byelorussian Academy of Engineering and Technology, and the Academy of Triboengineering of Ukraine, an Honorary Member of the Society of Tribologists of Belarus and STLE, a Fellow of ASME, IEEE, and the New York Academy of Sciences, and a Member of ASEE, Sigma Xi, and Tau Beta Pi. He has previously worked for Mechanical

Technology Inc., Latham, NY; SKF Industries Inc., King of Prussia, PA; IBM, Tucson, AZ; and IBM Almaden Research Center, San Jose, CA. He has held visiting professorship at University of California at Berkeley; University of Cambridge, UK; Technical University Vienna, Austria; University of Paris, Orsay; ETH Zurich; EPFL Lausanne; University of Southampton, UK; University of Kragujevac, Serbia; Tsinghua University, China; Harbin Institute of Technology China; and KFUPM, Saudi Arabia.

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