Green Energy and Technology

Michael Nosonovsky
Bharat Bhushan *Editors*

Green Tribology

Biomimetics, Energy Conservation and Sustainability

Springer

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Editors

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Biomimetics, Energy Conservation and Sustainability

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Preface

Tribology (from the Greek word τρίβω "tribo" meaning "to rub") is the interdisciplinary area of science and technology that involves the study of the interaction of solid surfaces in relative motion. Typical tribological studies cover friction, wear, lubrication, and adhesion. These studies involve the efforts of mechanical engineers, material scientists, chemists, and physicists. The word "tribology" was coined in the 1960s when it was realized that it may be beneficial for engineers and scientists studying friction, lubrication, and wear to collaborate in the framework of the new interdisciplinary area. Since then, many new areas of tribological studies have been suggested, which are at the interface of various scientific disciplines. These areas include nanotribology, biotribology, the tribology of magnetic storage devices, and micro/nanoelectromechanical systems. The research in these areas is driven mostly by the advent of new technologies and new experimental techniques for surfaces characterization.

Green tribology is a new, separate research area that is emerging, and it is defined as the science and technology of the tribological aspects of ecological balance and of environmental and biological impacts. There are a number of tribological problems that can be put under the umbrella of green tribology, and they are of mutual benefit to one another. These problems include tribological technology that mimics living nature (biomimetic surfaces) and thus is expected to be environment-friendly, the control of friction and wear that is of importance for energy conservation and conversion, environmental aspects of lubrication and surface modification techniques, and tribological aspects of green applications such as wind-power turbines, tidal turbines, or solar panels.

Since the 2000s, there have been several publications dealing with the economic and social implications of the ecological aspects of tribology. Most of these papers were prepared by economists and people involved in the strategic planning of research. The first scientific volume completely devoted to green tribology, which emphasized scientific rather than societal and economic aspects, appeared in 2010, and it was the theme issue of the Philosophical Transactions of the Royal Society, Series A (Volume 368, Number 1929) edited by M. Nosonovsky and B. Bhushan. In that volume, three areas of green tribology were identified:

biomimetic tribology, eco-friendly lubrication and materials, and tribological aspects of sustainable energy applications. The assumption was that combining these three areas, rather than focusing on narrow issues such as biodegradable lubrication, would mutually enhance them and establish new connections. Several workshops, conference sections, and symposia took place after that, which confirmed this inclusive approach, as well as the interest in green tribology in general.

The present publication in Springer to a certain degree extends that work: whereas some authors who participated in that volume also submitted their new results into the present volume, new authors participated as well. Prominent experts in various areas were invited that fit the definition of Green Tribology. The international group of authors include tribologists from the U.S., the U.K., Austria, Australia, Canada, India, South Africa, China, Israel, and Malaysia. Some of the authors are from academic institutions, while others are practical engineers from the industry. At University of Wisconsin–Milwaukee (UWM) a big group of tribologists has worked since 2009 on various aspects related to green tribology, and the results of their efforts are presented in the current volume. The biomimetic surfaces, including those using the Lotus, rose petal, gecko, and shark skin effects as well as tribology of human skin and hair were studied actively at the Ohio State University (OSU) in the past decade.

After a review of the current state of green tribology and its history, the main content of this book is divided into three parts. First, biomimetics in tribology is discussed, including biomimetic surfaces, materials, and methods. Biomimetic approaches follow the ways found in living nature and thus are expected to be eco-friendly. This includes non-adhesive surfaces mimicking flower (e.g., Lotus and rose) leaves, wetting transitions on these surfaces, biomimetic adhesion control for antifouling, polymeric and metal-based composite materials, and surfaces capable of friction-induced self-organization (self-lubrication, self-cleaning, and self-healing) as well as biomimetics in nanotribology. Second, green and sustainable materials and lubricants are reviewed. This involves water, ice, and natural oil-based lubrication, eco-friendly products for tribological applications involving natural fiber reinforced composites, fly ash, cements, and lubricant additives. The third part includes tribology of eco-friendly applications, such as wind turbines, biorefinaries, and marine wave energy collectors. Some of the chapters emphasize the review of the current state of the area, while others stress the research conducted by the investigators.

We would like to thank our colleagues, the authors, who responded to our invitations and contributed to this edited book. In addition, we would like to acknowledge help in preparation of the manuscripts of Ms. Caterina Runyon-Spears (OSU) and Mr. Mehdi Mortazavi (UWM).

July, 2011

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Chapter 5
Green Nanotribology and Sustainable Nanotribology in the Frame of the Global Challenges for Humankind

I. C. Gebeshuber

5.1 Introduction

This chapter deals with green and sustainable nanotribology. It highlights the challenges, development and opportunities of these new, emerging fields of science and embeds them in the major frame of the most serious problems we currently face on our planet. Fifteen global challenges are annually identified by the Millennium Project, a major undertaking that was started in 1996 and that incorporates organizations of the United Nations, governments, corporations, non-governmental organizations, universities and individuals from more than 50 countries from around the world. Green Nanotribology is of specific relevance when addressing Global Challenge 13 (Energy) and Global Challenge 14 (Science and Technology). These two challenges are introduced in more detail, and the contributions of Green Nanotribology to specifically address issues that arise due to these two challenges are outlined. Subsequently, the concept of sustainable nanotribology is introduced by correlating nanotribological developments with principles of sustainability identified by the US American Biomimicry Guild. Conclusions and outlook as well as recommendations round up the chapter.

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5.1.1 The "Most Serious Problems"

In 2005, Jared Diamond published his book 'Collapse: How societies choose to fail or succeed' [17]. In this work, Diamond identifies four major issues that lead to the collapse of societies. The first issue comprises destruction and loss of natural resources (e.g. destruction of natural habitats, aquacultures, biodiversity loss, erosion and soil damage), the second ceilings on natural resources (e.g. fossil fuels, water, photosynthesis ceiling), the third harmful things that we produce and move around (e.g. toxic man-made chemicals, alien species, ozone hole) and the fourth comprises population issues (e.g. population growth, impact of population on the environment). We need to go green if we want to sustain ourselves.

5.1.2 The "15 Global Challenges"

The Millennium Project was initiated in 1996. Until now, it has comprised the work of 2500 futurists, scholars, decision makers and business planners from over 50 countries. The project has nodes in 30 countries. The Millennium Project publishes the annual State of the Future Report (SOF) [36]. The SOF identifies and deals in detail with the fifteen major global challenges for humanity (Fig. 5.1), and provides an action plan for the world.

The 15 global challenges identified by the Millennium Project are:

1. How can sustainable development be achieved for all while addressing global climate change?
2. How can everyone have sufficient clean water without conflict?
3. How can population growth and resources be brought into balance?
4. How can genuine democracy emerge from authoritarian regimes?
5. How can policymaking be made more sensitive to global long-term perspectives?
6. How can the global convergence of information and communications technologies work for everyone?
7. How can ethical market economies be encouraged to help reduce the gap between rich and poor?
8. How can the threat of new and reemerging diseases and immune micro-organisms be reduced?
9. How can the capacity to decide be improved as the nature of work and institutions change?
10. How can shared values and new security strategies reduce ethnic conflicts, terrorism, and the use of weapons of mass destruction?
11. How can the changing status of women help improve the human condition?
12. How can transnational organized crime networks be stopped from becoming more powerful and sophisticated global enterprises?
13. How can growing energy demands be met safely and efficiently?

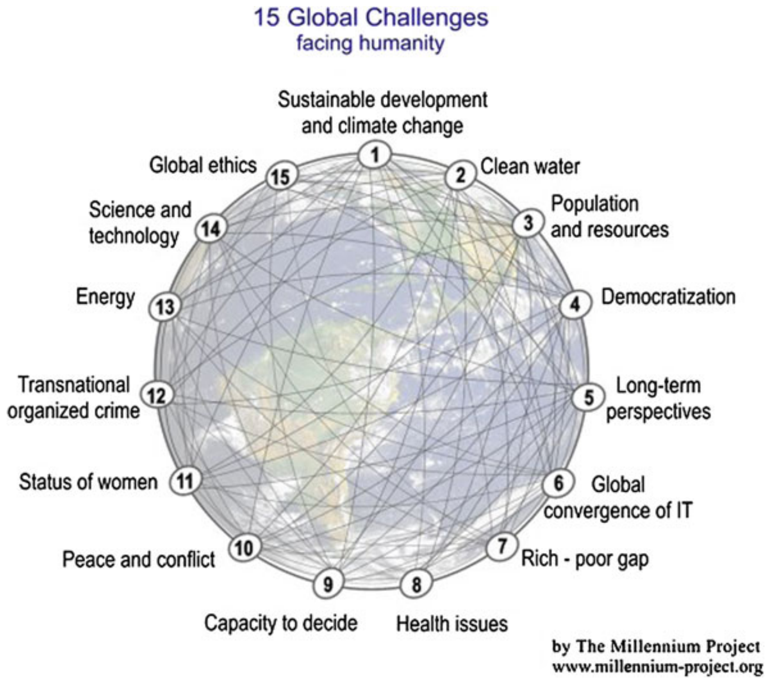

Fig. 5.1 15 Global challenges facing humanity as identified by the millennium project. Source: http://www.millennium-project.org/millennium/images/15-GC.jpg (last accessed 4 October 2011)

14. How can scientific and technological breakthroughs be accelerated to improve the human condition?
15. How can ethical considerations become more routinely incorporated into global decisions?

Green Nanotribology with all its beneficial consequences is of specific relevance for Global Challenge 13 (Energy) and Global Challenge 14 (Science and Technology).

5.2 Green (Nano-)Tribology

Si-wei Zhang, past chairman of the Chinese Tribology Institution, coined the term ‘Green Tribology’ and launched it as an international concept in June 2009.

> Green tribology is the science and technology of the tribological aspects of ecological balance and of environmental and biological impacts. Its main objectives are the saving of energy and materials and the enhancement of the environment and the quality of life (Peter Jost 2009, [2]).

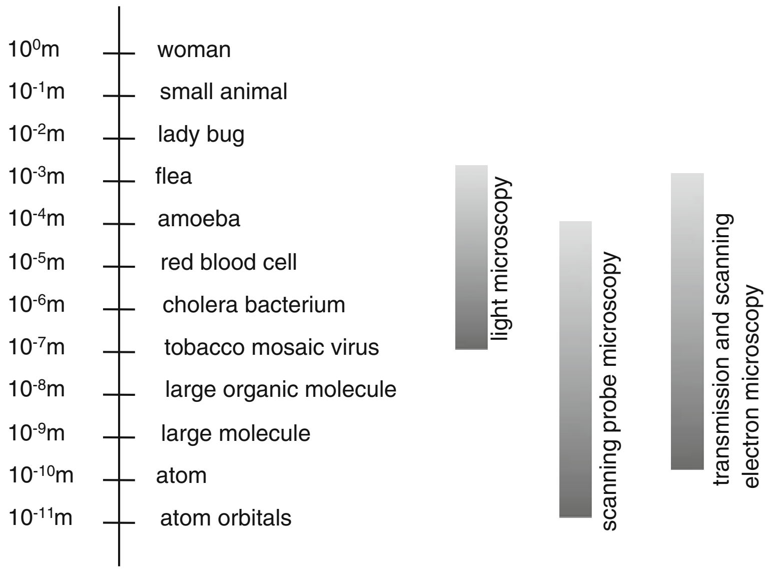

Fig. 5.2 From the macro- to the nanoscale. New types of microscopy allow for visualization and active interaction on very small scales, and therefore open up whole new domains for science and technology, e.g. nanotribology. © 2010 Springer [28]

We need green tribology because of the current pressures on energy, materials and food [58]. A focus on tribology might give breathing space while fuller solutions to environmental problems are being addressed [2]. Tribology must fall into line with the major politics of world environment and energy. Economic benefits derived from the application of tribology for the UK comprise £8–10 billion, out of which 60–70% would be energy related, all this largely from existing and applied research (innovation) [2].

Tribology covers all length scales. In this chapter, we concentrate on nanotribology (length scale some 10^{-9} nm). New types of microscopy now allow access to the nanocosmos, not just to view, but to interact (Fig. 5.2). This opens up completely new opportunities.

Nanotribology deals with nanosurfaces, nanoagents and nanoprocesses. For green nanosurfaces, points such as nanostructured surfaces, hierarchical surfaces, material selection, coated materials and monomolecular lubricant layers need to be addressed. The importance of nanosurfaces regarding Green Nanotribology is in the medium range. Of very high importance for Green Nanotribology are nanoagents. Points to address here are physical and chemical properties, the effect on the environment and biology, and the changes of the properties during the tribo-process. Regarding green nanoprocesses, the importance of points to address is in the medium to low range. Points to address comprise energy efficiency, the share between process relevant energy, destructive energy and waste and reusable energy as well as the effectiveness of reusing process energy [21].

In going green, tribology can benefit from a look at biology. Recently, biology has changed from being a highly descriptive science to a science that can be understood by engineers and researchers coming from the hard sciences, in terms of concepts, ideas, languages and approaches [24, 26]. In former times, tribology as well as biology used to be very descriptive. Inter- and transdisciplinary connections between the two fields were nearly impossible because of limited causal knowledge and limited causal relationships in both fields. This has changed. Today, we have increased causal knowledge [29] in both fields and therefore a promising area of overlap between tribology and biology [25, 30]. Causal knowledge indicates the fact that we know the relevant natural laws and can therefore construct explanations and forecasts. In biology, this is very often the case in physiology: We get cold feet when the vessels contract, *because* according to the laws of physics (fluid mechanics) less blood flows through these vessels (Drack, 2011, personal communication).

Biomimetics, the field that deals with knowledge transfer from biology to engineering and the arts, is a booming science that attracts more and more researchers, papers and attention [5, 48, 83]. Otto Schmitt [69], the inventor of the Schmitt trigger coined this field in 1982. One of the interesting aspects of such an interdisciplinary science as biomimetics is the variety of the publication channels. The author of this chapter for example has long been working in the field of bioinspired nanotribology and has published in journals as diverse as the Polish Botanical Journal (touching on the tribology of photosynthetic microorganisms with rigid parts in relative motion on the nanoscale) [78], Nano Today, elaborating on the tribology of biological hinges and interlocking devices, natural switchable adhesives and self-repairing molecules [22], the Proceedings of the Institution of Mechanical Engineers Part J: Journal of Engineering Tribology (touching on hinges and interlocking devices in microorganisms, [23]) and Tribology [25], proposing new ways of scientific publishing and accessing human knowledge inspired by transdisciplinary approaches regarding nanotribology. Biological best practice systems regarding nanotribology are functional and—in many cases—beautiful (Fig. 5.3).

Turning nanotribology green implies more than just the usage of sustainable additives [21]. Tribology is a systems science; therefore also the environment and the development with time have to be accounted for.

Nanoagents in tribology are additives, products of the additives and byproducts that appear in the system after the technological application. Reaction products (which can be harmful) have to be either chemically inert after use or are fed back to the system for further usage (waste-to-wealth concept). Not-used nanoagents need to be either inert or fed back to the reaction. Potentially harmful byproducts that have nothing to do with the initial nanoagent need to be either neutralized or re-used. Biomimetic tribological nanotechnology might help to turn nanotribology green, but it cannot be stated often enough that biomimetics does not automatically yield sustainable or even just green products [29].

Green control of friction, wear and lubrication on the nanoscale can be achieved by taking into consideration environmental aspects of nanoscale lubrication layers, environmental aspects of nanotechnological surface modification techniques and

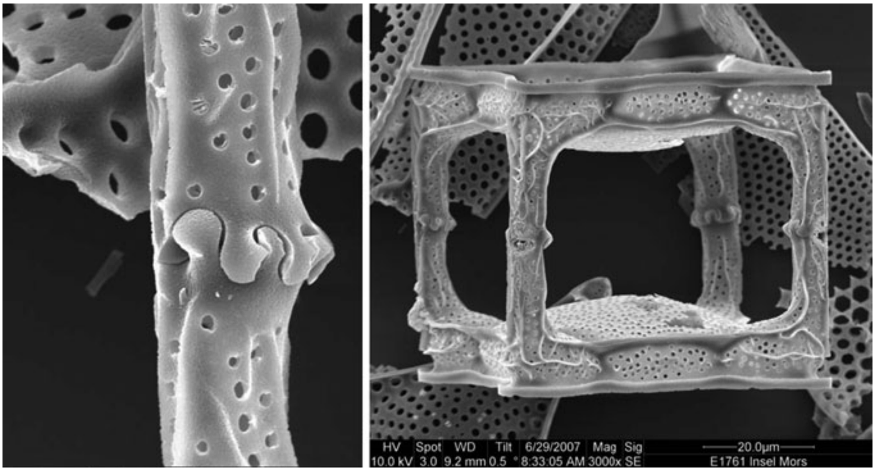

Fig. 5.3 This fossil diatom *Solium exsculptum* lived 45 millions of years ago on the island of Mors in Denmark. Scanning electron microscopy reveals unbroken diatom shells, with elaborate linking structures, and various micromechanical, incl. tribological, optimizations. © F. Hinz, Alfred Wegener Institute Bremerhaven, Germany. Image reproduced with permission

nanotribological aspects of green applications such as artificial photosynthesis. Questions that need to be addressed in turning nanotribology green are for example [21]:

- Do the processes get greener with the envisaged nanotribology (e.g. better coatings, less wear, less stiction)?
- Do the processes turn worse because of chemical reactions?
- Is the envisaged Green Nanotribology only pseudo-green, and in reality the negative impact on the environment/biology is only translated to other layers?

The usage of new technologies, materials and devices might increase advantages, but generates new problems. Exact eco-balance calculations need to be performed to prevent pseudo-green approaches. Biodiesel for example might be greener in the production than conventional products, yet still has technical concerns when used at concentrations greater than 5% [16].

5.3 The Relation of Green (Nano-)Tribology and "Global Challenge 13: Energy"

Issue: How can growing energy demand be met safely and efficiently?

The Millennium Projects annually publishes the State of the Future report (with few pages in print and vast information on CD) and has an extensive webpage (http://www.millennium-project.org). Concise information about this global challenge as well as the Executive Summary of the 2011 State of the Future report can be accessed online at http://www.millennium-project.org/millennium/Global_Challenges/chall-13.html and at http://www.millennium-project.org/millennium/SOF2011-English.pdf. The following quotations from the Millennium Project webpage on Global Challenge 13 give a glimpse on the points touched by the futurists:

> The world energy demand is expected to increase by between 40 and 50% over the next 25 years, with the vast majority of the increase being in China and India.
>
> G20 leaders pledged to phase out fossil fuel subsidies in the medium term.
>
> The World Bank estimates that countries with underperforming energy systems may lose up to 1–2% of growth potential every year, while billions of gallons of petroleum are wasted in traffic jams around the world.
>
> Massive saltwater irrigation can produce 7,600 L/ha-year of biofuels via halophyte plants and 200,000 L/ha-year via algae and cyanobacteria, instead of using less-efficient fresh-water biofuel production that has catastrophic effects on food supply and prices. Exxon announced its investment of $600 million to produce liquid transportation fuels from algae.
>
> CO_2 emissions from coal plants might be re-used to produce biofuels and perhaps carbon nanotubes. The global market value for liquid biofuel and bioenergy manufacturing is estimated at $102.5 billion in 2009 and is projected to grow to nearly $170.4 billion by 2014.
>
> Innovations are accelerating: concentrator photovoltaics that dramatically reduce costs; waste heat from power plants, human bodies, and microchips to produce electricity; genomics to create hydrogen-producing photosynthesis; buildings to produce more energy than consumed; solar energy to produce hydrogen; microbial fuel cells to generate electricity; and compact fluorescent light bulbs and light-emitting diodes to significantly conserve energy, as would nanotubes that conduct electricity. Solar farms can focus sunlight atop towers with Stirling engines and other generators. Estimates for the potential of wind energy continue to increase, but so do maintenance problems. Plastic nanotech photovoltaics printed on buildings and other surfaces could cut costs and increase efficiency. The transition to a hydrogen infrastructure may be too expensive and too late to affect climate change, while plug-in hybrids, flex-fuel, electric, and compressed air vehicles could provide alternatives to petroleum-only vehicles sooner. Unused nighttime power production could supply electric and plug-in hybrid cars. National unique all-electric car programs are being implemented in Denmark and Israel, with discussions being held in 30 other countries.

According to the Millennium Project, Global Challenge 13 will have been addressed seriously when the total energy production from environmentally benign processes surpasses other sources for five years in a row and when atmospheric CO_2 additions drop for at least five years.

Opportunities: Contribution of Green Nanotribology to meeting the energy demand safely and efficiently.

Energy is one of two global challenges identified by the Millennium Project where optimized tribology can substantially contribute. Opportunities regarding this challenge comprise renewable fuels, the use of waste energy and more efficient energy conversion systems. Regarding Green Nanotribology, energy management, wear management and self-healing coatings are of high potential.

Biofuels still have major unresolved tribological issues related to their hygroscopic properties and related absorption or adsorption of water, leading to microbiological activity, corrosion and fuel instability. These issues need to be addressed with tribology on all length scales. Furthermore, underperforming energy systems, MEMS energy harvesters and wind energy plants need to be tribologically optimized. Green Nanotribology can provide its share in all these areas.

5.4 The Relation of Green (Nano-)Tribology and "Global Challenge 14: Science and Technology"

Issue: How can scientific and technological breakthroughs be accelerated to improve the human condition?

The following quotations from the Millennium Project webpage on Global Challenge 14 gives a glimpse on the points touched by the futurists (http://www.millennium-project.org/millennium/Global_Challenges/chall-14.html):

> The acceleration of S and T innovations from improved instrumentation, communications among scientists, and synergies among nanotechnology, biotechnology, information technology, cognitive science, and quantum technology continues to fundamentally change the prospects for civilization.
>
> Nanobots the size of blood cells may one day enter the body to diagnose and provide therapies and internal VR imagery.
>
> Nanotechnology-based products have grown by 25% in the last year to over 800 items today for the release of medicine in the body, thin-film photovoltaics, super hard surfaces, and many lightweight strong objects.
>
> Despite these achievements, the risks from acceleration and globalization of S and T remain … and give rise to future ethical issues…
>
> The environmental health impacts of nanotech are in question.
>
> … supporting basic science is necessary to improve knowledge that applied science and technology draws on to improve the human condition.
>
> We need a global collective intelligence system to track S and T advances, forecast consequences, and document a range of views so that politicians and the public can understand the potential consequences of new S and T.

Scientific and technological breakthroughs need to be accelerated to improve the human condition. We currently have a major issue with over-information, and how to deal with it. Another issue relates to the major gaps between investors, innovators and inventors, regarding their goals and visions, dreams and approaches, reward systems and driving reasons. There is a need for new ways, concise visions and researchers who understand the big picture. There is a need for specialists who are coordinated by generalists.

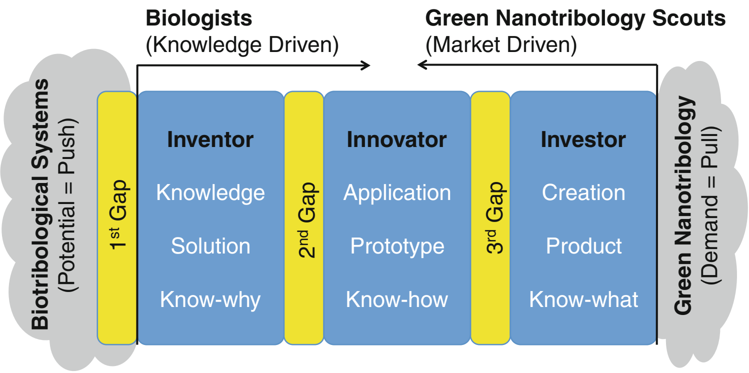

Fig. 5.4 The potential of Green Nanotribology in addressing Global Challenge 14, Science and Technology. See text

Questions that need to be addressed comprise: What good is science for if the work of scientists disappears in journals and books, and nobody applies it? What good is it if the scientists are only sustaining the publishing industry and/or serving the 'research market' and their results are hard/costly to access for the general public and the industry?

According to the Millennium Project, Global Challenge 14 will have been addressed seriously when the funding of R and D for societal needs reaches parity with funding for weapons and when an international science and technology organization is established that routinely connects world S and T knowledge for use in R and D priority setting and legislation.

Opportunities: Contribution of Green Nanotribology to accelerate scientific and technological breakthroughs to improve the human condition.

Sustainable Nanotribology ensures that there are no adverse environmental health impacts of nanotech on biology and the environment. Health impacts of nanotechnology are currently dealt with extensively [4, 12, 20, 40, 41, 62, 74–76, 79]. Green Nanotribology can, e.g. help address nanobot issues such as stiction and too high adhesion, emerging 3D MEMS tribology issues [66] and increase the quality of lab-on-a-chip devices. Micro- and nanotribological research has furthermore inspired a concept for a global collective intelligence system to track S and T advances [25] which might be extended to forecast consequences and to document a range of views, which is important regarding politics and governance.

Opportunities in science and technology are furthermore improvement of the human condition, aiming at having a context of knowledge and an equilibrium between generalists and specialists. The contribution of Green Nanotribology comprises establishment of a best practice example of a pipeline from the inventor to the innovator and the investor (Fig. 5.4). Nanobiotribological systems such as hinges and interlocking devices or self-repairing adhesives in diatoms [23, 34] or switchable adhesion exemplified by the selectin/integrin system [60] or the dry adhesives of the Gecko foot [3] are just some examples of the treasure box of best practice examples for the green nanotribologist looking for inspiration in nature. They provide the potential (push, Fig. 5.4). Between this world of solutions, of examples, of best practices, and the world of the scientists and developers, the inventors, is the first gap (Fig. 5.4). Knowledge–driven biologists head out and try to reach tribologists, offering their solutions. This happens with increasing success. Wilhelm Barthlott likes to tell the story that he went for 11 years from one company to the next, with a lotus leaf in his hands, trying to sell the purity of the sacred lotus [6] as something that is interesting for technology. He was ignored, until finally the company STO realized the potential of self-cleaning paints. Barthlott is now a well-off man, the lotus effect is well known, even in the general public, and biomimetics is a field with very positive connotations. The next gap is between the inventor and the innovator (How do the research results become prototypes? Who identifies promising designs/developments and promotes commercialization?), and the third gap is between the innovator and the investor (How do the prototypes translate into marketable products? Who ‘sells’ the prototypes to industry? Who does the communication between researchers and developers and industry?). From the technology side, market-driven green nanotribologists head out to screen beyond the gaps, and identify people from other fields to work with, and fulfill the demand (pull) of the market (Fig. 5.4). What we need is a pipeline from knowledge via the application to the creation, from the solution via the prototype to the product, and from the know-why via the know-how to the know-what.

5.5 Bioinspired Optimization Levers in Green Nanotribology

Scherge and Rehl [68] identified four optimization levers in tribology: breaking-in, additives, finishing and material selection. Green Nanotribology can address all these four levers [21]: (1) The key advance of biomimetic Green Nanotribology is in the area of breaking-in. Our current technological systems and devices are sequentially produced and need ‘breaking-in’. Organisms that are growing from a nucleus on the other hand need ‘initial consolidation’. Contrary to the process of breaking-in, the initial consolidation in organisms is equivalent to a ‘peak’ that establishes function and controls quality via ‘hail or fail’. Biological systems mainly have soft materials and use water-based lubricants; they have tribological properties in many cases superior to the ones of technical devices and can serve as inspiration for new tribological approaches. (2) Examples for additives in biological lubricants are proteins, e.g. in the mucus of snails (which acts as adhesive and lubricant, [46]) and in fish mucus (which, amongst other functions, reduces drag, [13, 42, 51]) as well as in synovial joints (hip, knee, shoulder, [54]). Biological lubricants are water soluble. Currently, various research projects aim at the development of water-soluble lubricants for technological applications (e.g. by the V.A. Kargin Polymer Chemistry and Technology Research Institute or by the Singapore Institute of Manufacturing Technology). Environmental compliance and improved tribological properties could go hand-in-hand. (3) Nature's materials are complex, multi-functional, hierarchical and responsive and in most instances functionality on the nanoscale is combined with performance on the macroscale. Biological materials have elaborate surface textures and finishing: the finishing of biological tribosurfaces has been the focus of investigation in major research networks, and the literature is bursting with examples of soft matter with excellent finishing. Examples comprise hierarchical surface structures down to the nanoscale in the sand skink [8], in snake skin [39], in the surface of the mammal eye [14]. Optimized surfaces might render the use of lubricants obsolete, and would be a most elegant way to approach tribology issues. (4) The optimization lever 'material selection' is of utmost importance in biological nanotribology. The correlation of structure and function and structure and material need not be forgotten in this regard. In biology, few chemical elements and few different materials are used; these materials are either slightly changed to obtain added value and to fulfill various functions (cf. collagen) and/or they are structured, in some cases even hierarchically. Diatoms [65] are excellent examples from nature for tribological optimization under limited material variety conditions [23, 32].

5.6 Goals for Effective Green Nanotribology

Goals for effective Green Nanotribology are located in three main areas: Production (agents), reaction (agents; object to nanoproduct; waste agents direct effects) and nanoproduct life cycle (effects on the environment during the service period and during degradation). In the production the goal is minimum pollution, in the reaction the goal is to keep the reaction only where it needs to be and not beyond, and in the life cycle care has to be taken to ensure minimum influence on substances and improved degradation characteristics (e.g. via a decay booster).

5.7 Sustainable Nanotribology

The distinction between 'green' and 'sustainable' can best be explained with the example of wood. Wood is green, but if it comes from the rainforest and not from plantations it is not sustainable. Not everything that is green is sustainable, and not everything that is sustainable is green.

In this section we develop a concept of Sustainable Nanotribology inspired by 'Life's Principles' (Table 5.1) as introduced by the U.S. American 'Biomimicry Guild'. The Biomimicry Guild has been combining sustainability and biomimetics from their very beginnings at the end of the 1990s, stating that these two have to be inseparably connected. Other researchers state that biomimicry is a design method, and as such is independent from a value such as sustainability [29].

Table 5.1 Life's principles as established by the Biomimicry Guild (http://www.biomimicryguild.com/) can provide a guide towards rendering nanotribology green

Life's principles–design lessons from nature
1. Earth's operating conditions:
1.1. Water-based
1.2. Subject to limits and boundaries
1.3. In a state of dynamic non-equilibrium
2. Life creates conditions conducive to life
2.1. Optimizes rather than maximizes
2.1.1. Multi-functional design
2.1.2. Fits form to function
2.1.3. Recycles all materials
2.2. Leverages interdependence
2.2.1. Fosters cooperative relationships
2.2.2. Self-organizing
2.3. Benign manufacturing
2.3.1. Life-friendly materials
2.3.2. Water-based chemistry
2.3.3. Self-assembly
3. Life adapts and evolves
3.1. Locally attuned and responsive
3.1.1. Resourceful and opportunistic
3.1.1.1. Shape rather than material
3.1.1.2. Simple, common building blocks
3.1.1.3. Free energy
3.1.2. Feedback loops
3.1.2.1. Antennae, signal, response
3.1.2.2. Learns and imitates
3.2. Integrates cyclic processes
3.2.1. Feedback loops
3.2.2. Cross-pollination and mutation
3.3. Resilient
3.3.1. Diverse
3.3.2. Decentralized and distributed
3.3.3. Redundant

The Biomimicry Guild webpage (http://www.biomimicryguild.com) gives six categories for sustainable biomimetics, each with various subcategories. In the following, we correlate this list with nanotribology, identify applications in green nanotribology and give tribological examples where these principles are already incorporated (research, prototype or device stage).

1. Evolve to survive

Principle: Sustainability can be ensured when information to ensure enduring performance is continually incorporated and embedded.

Application in Green Nanotribology: Keeping nanotribology state-of-the art. Continuous implementation of the most recent research and development results ensures continuous optimization of nanotribological materials, structures and processes.

There are three major ways to implement this principle: (1) *When strategies that work are replicated, when successful approaches are repeated*. Implications for Green Nanotribology would be biomimetic approaches, learning from nature, looking at natural biotribological model systems (best practices) and learn from them [22, 27, 30, 31]. (2) *When the unexpected is integrated*. In biology, the incorporation of mistakes in ways that can lead to new forms and functions turned out to be highly successful. Regarding Green Nanotribology, this way could be implemented by policies that allow for tribological research along unconventional paths, by responsible and environmentally concerned researchers. (3) *Exchange and alteration of information* (*reshuffling of information*). In biology this implementation has highly successful examples in bacteria (e.g. gene swapping, [61]). Concerning Green Nanotribology the implications would be biomimetics, learning from nature and tribology–related research and development directed by deep understanding of the underlying principles.

2. Resource efficiency regarding material and energy

Principle: Skillfully and conservatively take advantage of local resources and opportunities.

Application in Green Nanotribology: Keeping the tribosystem closed, reusing and recycling of substances and of waste energy.

There are four major ways to implement this principle: (1) *Multi-functional design ensures the meeting of multiple needs with one solution*. Comparable to the pluripotency of stem cells, for example surface textures or formulations of additives or tribological processes can be designed in a way that is sustainable. If now the textures, formulations and processes are pluripotent, and can easily be adjusted for the respective tribosystem, the advantage would be that there are already established green routes of production, usage and disposal, and no new research to make the new approaches green would have to be performed. In nature, we have very often just slight variations in the same material, structure or function, to accommodate totally different needs. One example is collagen that occurs in bones, skin, tendons and the cornea [67]. (2) *The usage of low energy processes ensures minimum energy consumption*. This can be realized, e.g. by temperature, pressure or time reduction. One fabulous example from nature is biomineralization. More than 60 different minerals are produced by organisms, at ambient conditions—ceramics in our teeth, magnets in bacteria or silica in diatoms are just some examples [9, 70]. (3) *Recycling of all materials keeps materials in a closed loop*. Food chains in biology are exquisite examples for closed-loop materials usage. Concerning Green Nanotribology, closed tribosystems, reuse of energy and material as well as recycling are of relevance. (4) *The selection for shape or pattern based on need ensures the fit of form to function*. In biology, structure–function relationships are omnipresent [71, 72, 77]. Especially in natural micro-and nanotribological systems, e.g. hinges and interlocking devices in diatoms, this relationship is obvious, and can serve as inspiration for new and emerging man-made micro- and nanotribological systems [23, 32, 33].

3. Adaptation to changing conditions

Principle: Appropriately respond to dynamic contexts.

Application in Green Nanotribology: Multifunctional responsive nanosurfaces, nanoagents and nanoprocesses that change dependent on the environment and that are used in amounts as minimal as necessary.

There are three major ways to implement this principle: (1) *The maintenance of integrity through self-renewal ensures persistency by constantly adding energy and matter to the system*. This energy and matter is subsequently used to heal/ repair and improve the system. Passive and active tribological systems such as self-repairing adhesives or anti-corrosion layers are the respective examples from tribology [1, 35, 47, 81]. (2) *Resilience through variation, redundancy and decentralization ensures the maintenance of function following disturbance*. (Resilience—as defined by http://www.wordnet.princeton.edu—denotes the physical property of a material that can return to its original shape or position after deformation that does not exceed its elastic limit). In biology this is achieved by the incorporation of a variety of duplicate forms, processes or systems that are not exclusively located together. In the concept development of Sustainable Nanotribology, implementation of this feature might prove complicated, and some additional brainstorming might be necessary to identify tribologically relevant biological best practices and the related translation to engineering. (3) *The incorporation of diversity (inclusion of multiple forms, processes or systems) to meet a functional need has proven highly successful in biology*. Examples can be found on all scales, from single biomolecules (size some nanometers) to tissues and limbs (size some centimeters) to whole organisms and ecosystems. Nanodiversity as a concept in nanotribology was just recently introduced as one of the major goals for effective Green Nanotribology [21] and should be developed further towards sustainability.

4. Integration of development with growth

Principle: Invest optimally in strategies that promote both development and growth.

Application in Green Nanotribology: New research and development in sustainable nanotribology should not just be concerned with growth and revenue—even when profits are high, a balance has to be sought between development and growth—new research results have to be implemented, even if it is not beneficial for the economy in the short run—because in the long run only sustainable approaches ensure our survival [17].

There are three major ways to implement this principle: (1) *The combination of modular and nested components progressively fits multiple units within each other, from simple to complex*. In biology, hierarchy and multifunctionality can be seen in many organisms ([49, 82, 19]). In tribology, and especially in nanotribology, we have just started to develop such elaborate approaches, e.g. nanotribological multiscale friction mechanisms and hierarchical surfaces [55]. (2) *Building from the bottom up allows the use of code, work with molecular building blocks and inclusion of functionalities*. Organisms are all built bottom–up, our current technology, however, is still in most cases using top–down techniques [11]. The development and successful application of nanotribological bottom–up approaches would be of highest interest, since one of the important levers of optimization lies in surface finishing [21]. (3) *Self-organization, the creation of globally coherent patterns from just local interactions, with no central control unit*. Realizations of this implementation can be seen on all length scales in biology, from single molecules to social behavior. In Green Nanotribology it would be beneficial if the tribosystem would locally react according to varying demands, being only as good as necessary, and not as good as possible.

5. Responsiveness and being locally attuned

Principle: Fit into and integrate with the surrounding environment.

Application in Green Nanotribology: Sometimes we overdo it with our current technology. Sometimes our systems are too good, too expensive, too anything. Responsive Green Nanotribological systems would be just as good as necessary, with additional benefits of energy saving and even greater environmental soundness.

There are four major ways to implement this principle: (1) *Usage of readily available materials and energy*. Implementation of this principle ensures building with abundant, accessible materials, while harnessing freely available energy [59, 63]. A possible realization of this would be flexible nanotribology that uses only readily available materials and energy. (2) *The cultivation of cooperative relationships finds value through win–win interactions*. This aspect is omnipresent in biology, and lacks in current technology. Again, this might be a point where brainstorming could yield some interesting new approaches. (3) *The leverage of cyclic processes takes advantage of phenomena that repeat themselves*. Also this aspect is omnipresent in biology, and lacks in current technology. Brainstorming for new approaches is necessary. (4) *The use of feedback loops engages in cyclic information flows to modify a reaction appropriately*. Reinforcement via feedback loops is important and is applied in biology and in technology [15, 37, 73]. Regarding nanoprocesses, we are just beginning to apply cyclic information flows [43, 52, 53].

6. Usage of life-friendly chemistry

Principle: Use chemistry that supports life processes.

Application in Green Nanotribology: Green chemistry is a prerequisite for Green Nanotribology [21, 56, 57].

There are three major ways to implement this principle: (1) *Building selectively with a small subset of elements* (*assembly of relatively few elements in elegant ways*). This principle is strongly implemented in biology. In biological materials, just a couple of elements are used in major amounts, and even just a couple of

Table 5.2 Major goals for effective Green Nanotribology and how it can benefit from biology [21]

Green Nanotribology major goals		Importance	Nature's solutions
Optimized system energy balance	Minimizing destructive energy	Medium	Water–based lubricants; Predetermined breaking points; Responsive marerials; Structure rather than material
	Shield tribosystem against damaging consequences	High	Integration intstead of additive construction; Optimization of the whole instead of maximization of a single component future; Multi-functionality instead of mono-functionality; Energy efficiency; Development via trial-and-error processes
	Reuse energy and neutralize waste energy	Low	Organisms
Protection of the environment from process residues	Unused agents	Low	Reuse in the ecosystem
	Pollutants	Medium	Biodegradability; Confined spaces for chemical processes
	Process reliability and worst case scenario dangers	High	Highly developed over time (evolution)
Environmental cost of the process itself	Effort to produce agents	High	Optimized (on system level)
	Purer inputs with more waste in the preparation	Medium	Water-based chemistry; Cell organelles serve as nano factories; Shielding of process via membranes
	Different economy of scale	Low	Major evolutionary transitions; Mammals versus cold-blooded animals
Preservation of nanodiversity		Unknown	Additives in ultra-low concentration ensure nanodiversity; Reuse of the same base material with slight modifications for various applications

chemical compounds. Especially in small biological entities (some molecules, nanotextured surfaces, nanostructures, etc.) the structure rather than the material determines the function [18, 44, 64]. This goes as far as properties of biological entities that rely on structure alone. One impressive example in this regard are structural colors, where the coloration does not come from pigments but from minuscule structures with sizes on the order of the wavelength of visible light, generating colors by physical mechanisms such as diffraction, scattering and interference (see e.g. [10, 45, 50, 84]). One impressive example from biology for building with a small subset of elements are the diatoms, unicellular algae with a skeleton made from silica (see Fig. 5.3, [65]). The silica is structured with various functional levels of hierarchy, it is micromechanically optimized [38], has optical properties that are of high interest for nanotechnology [84] and is produced in ambient conditions which makes it interesting for nanoengineers attempting to build structures with intrinsic functions at ambient conditions and with life-friendly chemistry. (2) *Breaking down of products into benign constituents using chemistry in which decomposition results in no harmful by-products*. Nature does it this way, and we with our current technology are still far away from doing it this way—although regarding going green it would be very beneficial. In green nanotribology, we could start another attempt to develop entities that decompose into harmless end products [21]. (3) *Water is the generally used solvent in the chemistry of life*. Such water-based approaches are slowly starting to enter our current technology. In their 2004 article in Nature on the nonlinear nature of friction, Israelachvili and co-workers stress that current oil-based lubricants are by far outclassed by the water-based lubricants used in nature [80]. The hip joint with its amazingly low friction coefficient is one of the examples from nature on highly efficient tribosystems lubricated with water-based chemistry [54].

The goals of Green Nanotribology are to provide technical support to the preservation of resources and energy and to propel the society forward towards sustainability.

The goals of Green Nanotribology and how it can benefit from biology can be grouped into four categories (Table 5.2). The best practices from nature listed in Table 5.2 are highly diverse and show a multitude of different approaches that can be learnt from.

5.8 Conclusions and Outlook

Green Nanotribology and Sustainable Nanotribology have high potential in science and technology. Tribology together with the other fields of engineering will increasingly aim at providing sustainable solutions. We need to establish ethical codes of conduct for using novel technologies, to make the transition smooth and well rounded. Successful tribologists are inherently transdisciplinary thinkers—this is needed in our increasingly complex world. Tribologists will successfully contribute to address major global challenges.

The Sustainable Nanotribology concept developed in this book chapter is inspired by life's principles as introduced by the Biomimicry Guild. Open points regarding Sustainable Nanotribology touch upon adaptation to changing conditions and responsiveness and being locally attuned: Resilience through variation, redundancy and decentralization that ensure the maintenance of function following disturbance as well as the cultivation of cooperative relationships that finds value through win–win interactions as well as the leverage of cyclic processes that takes advantage of phenomena that repeat themselves need to be implemented in the concept. Including the sustainability approach as introduced by Albert Bartlett [7] can help refine the concept further, yielding Sustainable Nanotribology for society.

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Editor's Biography

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 at Boulder in 1973 and 1976, respectively, an MBA 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 Honouris Causa from the National Academy of Sciences at Gomel, Belarus in 2000. He is a registered professional engineer. He is presently an Ohio Eminent Scholar and The Howard D. Winbigler Professor in the College of Engineering, and the Director of the Nanoprobe Laboratory for Bio- & Nanotechnology and Biomimetics (NLB^2) at the Ohio State University, Columbus, Ohio. His research interests include fundamental studies with a focus on scanning probe techniques in the interdisciplinary areas of bio/nanotribology, bio/nanomechanics and bio/nanomaterials characterization, and applications to bio/nanotechnology and biomimetics. He is an internationally recognized expert on bio/nanotribology and bio/nanomechanics using scanning probe microscopy, and is one of the most prolific authors. He is considered by some as a pioneer of the tribology and mechanics of magnetic storage devices. He has authored 7 scientific books, more than 90 handbook chapters, more than 700 scientific papers (h-index—52+; ISI Highly Cited in Materials Science, since 2007), and more than 60 technical reports, edited more than 50 books, and holds 17 US and foreign

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patents. He is co-editor of Springer NanoScience and Technology Series and co-editor of Microsystem Technologies. He has given more than 400 invited presentations on six continents and more than 160 keynote/plenary addresses at major international conferences.

Dr. Bhushan is an accomplished organizer. He organized the first symposium on Tribology and Mechanics of Magnetic Storage Systems in 1984 and the first international symposium on Advances in Information Storage Systems in 1990, both of which are now held annually. 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 and has received more than two dozen awards for his contributions to science and technology from professional societies, industry, and US government agencies. 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 the 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, a fellow of ASME, IEEE, STLE, and the New York Academy of Sciences, and a member of ASEE, Sigma Xi, and Tau Beta Pi.

Dr. Bhushan has previously worked for the R&D Division of Mechanical Technology Inc., Latham, NY; the Technology Services Division of SKF Industries Inc., King of Prussia, PA; the General Products Division Laboratory of IBM Corporation, Tucson, AZ; and the Almaden Research Center of IBM Corporation, San Jose, CA. He has held visiting professor appointments at University of California at Berkeley, University of Cambridge, UK, Technical University Vienna, Austria, University of Paris, Orsay, ETH Zurich, and EPFL Lausanne.

Michael Nosonovsky is an Assistant Professor at University of Wisconsin–Milwaukee. He got his M.Sc. from St. Petersburg Polytechnic University (Russia) and Ph.D. from Northeastern University (Boston). After that he worked at Ohio State University and National Institute of Standards and Technology. His interests include biomimetic surfaces, capillary effects, nanotribology, and friction-induced self-organization. Among his research findings are:

- Multiscale roughness can stabilize a composite superhydro/oleophobic interface, which is used for new omniphobic surfaces.

- Friction-induced vibrations and instabilities of various types can lead to self-organized structures (e.g., protective in situ tribofilms), and the phenomenon is investigated by non-equilibrium thermodynamics. The transient running-in process can be treated as self-organization (since surfaces adjust to each other) in accordance with the minimum entropy production theorem. Multiscale thermodynamic models of self-healing materials bridged the gap between the theories of self-organization and practical efforts in synthesizing self-healing materials.
- Empirical laws of friction and wear (irreversible energy dissipation and material deterioration) are consequences of the 2nd law of thermodynamics, and thus friction is a fundamental physical phenomenon rather than a collection of various unrelated mechanisms.
- Pressure in condensed water capillary bridges between nanoasperities is deeply negative (tensile stress), possibly showing the world record of negative pressure in water (-150 MPa).

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