Materials Forming, Machining and Tribology

J. Paulo Davim *Editor*

Ecotribology

Research Developments

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Preface

In the recent years, ecotribology (or environmentally friendly tribology) has gained increasing importance in green science and engineering. It is current report ecotribology or green tribology, as environmentally acceptable tribological practices, namely *savings of resources of energy and materials, optimizing product usage and design, reducing energy consumption and the impact on the environment.* Today, it is normal to include several topics under the umbrella of ecotribology, namely biomimetics surfaces, control of friction and wear, biolubricants, environmental aspects of lubrication and surface modification techniques as well as tribological aspects of green applications, such as wind-power turbines, or solar panels.

The purpose of this book is to present a collection of examples illustrating review studies and research in ecotribology. Chapter 1 of the book provides ecotribology development, prospects, and challenges. Chapter 2 is dedicated to advancements in ecofriendly lubricants for tribological applications (past, present, and future). Chapter 3 describes new emerging self-lubricating metal matrix composites for tribological applications. Chapter 4 contains information about multi-objective optimization of engine parameters with biolubricant-biofuel combination of VCR engine using Taguchi–Grey approach. Chapter 5 describes biolubricants and potential of waste cooking oil. Finally, Chap. 6 is dedicated to two-body abrasion of bamboo fiber/epoxy composites.

The present book can be used as a research book for a final undergraduate engineering course or as a topic on tribology at the postgraduate level. Also, this book can serve as a useful reference for academics, researchers, mechanical, materials and industrial engineers, professionals in tribology and related industries. The scientific interest in this book is evident for many important centers of research, laboratories, and universities as well as industry. Therefore, it is hoped this book will inspire and enthuse others to undertake research in ecotribology.

The Editor acknowledges Springer for this opportunity and for their enthusiastic and professional support. Finally, I would like to thank all the chapter authors for their availability for this work.

Aveiro, Portugal J. Paulo Davim
October 2015

Contents

Chapter 1
Ecotribology: Development, Prospects, and Challenges

Ille C. Gebeshuber

Abstract Ecotribology is gaining increasing attention. Our view of the environment has changed from regarding it as a constant that provides resources and acts as a sink for waste toward a more complex view, where the environment is seen as a variable that can be influenced by our activities and on which we are utterly dependent. Ecotribology can be seen as the answer to this changed role of the environment. In the very word *ecotribology* economical and ecological aspects meet, and indeed the field comprises green tribology, sustainability, ecological aspects, economical aspects, environmentally compatible lubricants, environmentally friendly tribology, tribology of eco-friendly applications, tribology for energy conservation, tribology for life, and renewable energy tribology. This chapter deals with components, goals, optimization levers, challenges, and prospects of ecotribological systems and gives ample examples in which regard we can learn from living nature via biomimetic approaches to achieve efficient ecotribology, concerning materials, structures, and processes.

1 Introduction

Ecotribology is gaining increasing attention. Our view of the environment has changed from regarding it as a constant that provides resources and acts as a sink for waste toward a more complex view, where the environment is seen as a variable that can be influenced by our activities (cf. industrialization, species extinction [8, 9], global challenges [43]) and on which we are utterly dependent. Peter F. Jost

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said at the 4th World Tribology Congress in Kyoto, Japan, in 2009 that a focus on tribology might give “breathing space” while comprehensive solutions to environmental problems were being addressed and suggested that tribology must fall in line with the major politics of world environment and energy [6]. Ecotribology can be seen as the answer to this changed role of the environment. In the very word *ecotribology* economical and ecological aspects meet, and indeed the field comprises green tribology, sustainability, ecological aspects, economical aspects, environmentally compatible lubricants, environmentally friendly tribology, tribology of eco-friendly applications, tribology for energy conservation, tribology for life, and renewable energy tribology.

In 2006, Bartz published a paper in Tribology International where he gave in dense bullet form environmentally acceptable tribological practices (see Sects. 3.2 and 3.3 for related further elaboration). Sasaki in 2010 published a paper called “Environmentally friendly tribology (Ecotribology).” Sasaki sees the need for ecotribology based on global warming and increased pollution and suggests multiscale texturing and diamond-like carbon (DLC) coatings for green lubrication as prospects for ecotribology [78]. In the 2012 book “Green Tribology: Biomimetics, Energy Conservation and Sustainability” [66] specific focus is taken on biomimetic surfaces, materials, and methods as well as green and sustainable lubricants and materials, as well as applications.

This chapter takes the whole approach further, and introduces in Sect. 4 the concept of biomimetic metal management for tribology, inspired by materials, structures, and processes in living nature.

2 Motivation

Humans are one of the most successful, if not the most successful species on Earth. Our numbers rise and rise, and the rate of technological advancement is astonishing. If one looks at the age of the Earth compressed into a time span of 1 year, with today being midnight, December 31, the industrial revolution has only started 2 s before midnight. During this relatively short time, we have developed internal combustion engines, computers, spaceships, and chess- and table tennis playing robots. As many benefits as this development has, there are various drawbacks that increasingly cannot be ignored anymore. Pollution, habitat destruction followed by species extinction on a massive scale, climate change, and increasing problems with resistant microorganisms directly result from our current way of resource management and doing engineering. The global challenges [42] cannot be ignored anymore, as cannot be ignored that we might have brought our planet close to a tipping point [8] and have unleashed the sixth mass extinction of species [9], with mass extinction being defined that 80 % of all species go extinct. The last mass extinction of species was 55 millions of years ago, when the dinosaurs disappeared.

In about 1760, when coal started to be used as an energy source (before only renewable natural energy was used), only 2 s before midnight (which represents today) in the condensed view introduced above (Fig. 1), the industrial revolution started—and with it the current rise of Carbon dioxide in the atmosphere. That time, production methods started to transit from handmade to machine-made. Another major change took place in the mid 1850s, with the beginning of commercial drilling and production of petroleum.

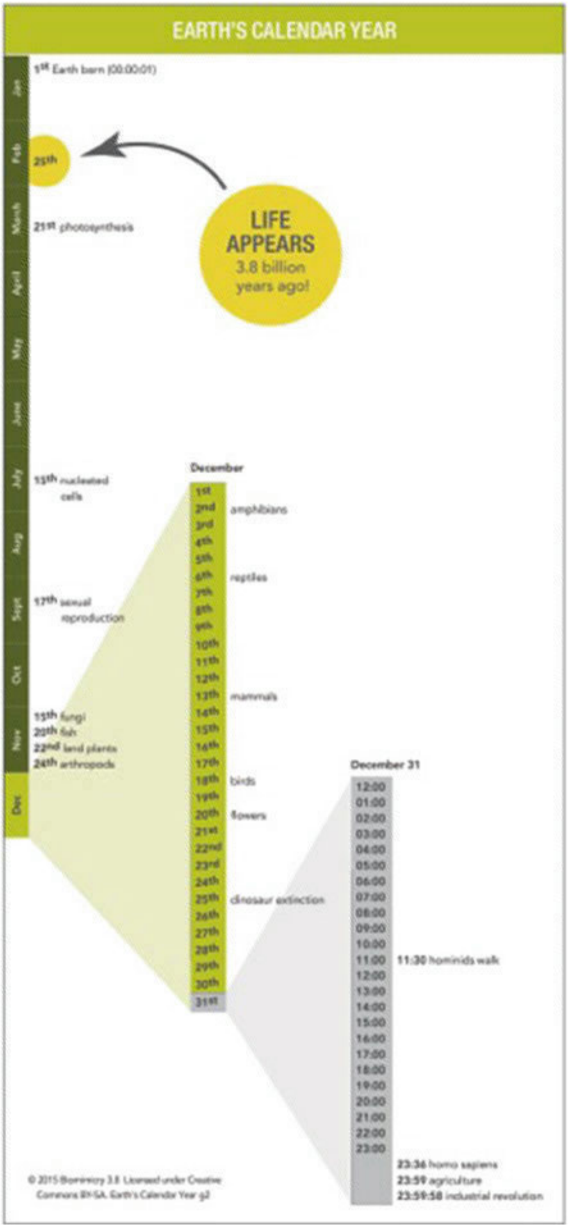

Fig. 1 History of the Earth condensed to 1 year. © 2015 Biomimicry 3.8 licensed under creative commons BY-SA

Increasingly replacing current technologies and approaches with sustainable and green technologies might substantially contribute to successfully address these problems and challenges. We need to take action. In our current world, where economic aspects are of paramount importance, ecological challenges can only be addressed when the approach is economically fruitful. And exactly here the concept of ecotribology, in which ecological and economical aspects are interwoven, becomes so important. Another advantage of tribology as opposed to various other, more theoretical approaches, is its inherent application orientation. Prof. Jost, the president of the International Tribology Council, mentioned in his opening address at the World Tribology Congress 2009 in Kyoto that a focus on tribology might give breathing space while fuller solutions to environmental problems are being addressed. Tribology must fall into line with the major politics of world environment and energy.

3 Efficient Ecotribological Systems

3.1 Components of Efficient Ecotribological Systems

Efficient ecotribologial components (Table 1) are ecologically and economically justifiable. The introduction of a concept of the *cost* of our current approaches for future generations would cause a shift in our perception, and might leapfrog our society toward sustainability. If one watches the web of life through time as an optimized tribosystem (thought experiment) the first interesting aspect that comes to mind is the very low amount of different materials that are used. *Structures rather than material* is a deep principle that can be extracted when analyzing plants, animals, humans, and microorganisms. Structures from the living world (such as bone and wood) are highly elaborate, with up to 11 hierarchical layers, with added functionality on each layer. The information for the materials, and the structures, as well as for the surfaces, agents, and processes used in living nature is inscribed in genomes, in combination with their interaction with the environment. Development of a similar approach to machines, processes, and systems in our technological world might be worth thinking about. We have just started to develop machines that self-assemble, self-repair, warn, and disassemble when needed or wanted. We have (apart from computer codes) nothing only slightly similar to a genetic code in our machines. No resemblance of phenotype and genotype, let alone developmental plasticity and adaptations to the environment, and also to their changes with time. Programmable materials (without emergent dangerous properties) might be a very interesting and promising way to start to address our current problems.

Slowly we are starting to develop synthetic materials that sense and respond to external stimuli and react to environmental parameters such as temperature and chemical composition, by changing their chemistry and/or shape, and thereby their functionality and performance (see Soft Matter Special Issue “Reconfigurable soft

Table 1 Components of ecotribological systems

Category	Importance	Challenges for R&D, in brackets selected exemplary publications treated in detail in the text and in Table 2
Materials	Medium	Optimization of shape rather than material
		Use of a limited amount of materials, slightly chemically varied and smartly structured Less use of metals [56]
		Tailored materials with response to the conditions of the tribosystem, as good as necessary, not as good as possible
		Benign materials
		Biomined metals (see Sect. 4.1)
		Recyclable materials
		Materials with an *expiration date*
		Triggered materials [82]
Structures	High	Smart structures
		Reactive structures [82]
		Biomimetic functional structures (see Sect. 4.2)
		Hierarchical structures
		Time-limited arrangements [95]
		Programmed structures [85]
		Self-assembled structures
		Directed assembly of structures [15]
		3D printed structures
		Foldable structures [1]
Surfaces	Medium	Structured surfaces [1]
		Hierarchical surfaces
		Texture rather than material
		Coatings
		Additive layers
Agents	High	Physical and chemical properties
		Effect on the environment
		Effect on organisms [64]
		Temporal changes of properties [40]
		Changes of properties in the triboprocess [89]
Processes	Medium to low	Energy efficiency
		Chemically guided synthesis of functional structures and materials (see Sect. 4.3)
		Fraction of process relevant energy, destructive energy and waste as well as recyclable energy
		Efficiency of reusability of process energy

matter", edited by Balazs and Aizenberg [7]). The coupling between mechanical, electrical, optical, or thermal behavior in such reconfigurable materials promises exciting applications in ecotribology.

In the following, we introduce eight key papers from the above-mentioned special issue, relate them to components of ecotribological systems (Tables 2 and 3) and highlight potential advantages from such new approaches. The methodology of this approach is inspired by the transdisciplinary knowledge integration method [45, 51] and innovision, a method developed by the author of this chapter [29, 30]. "Innovision is a new method to do research and to think. The path from innovation to innovision is characterized by the development of a new framework of thinking that is the prerequisite for the provision of solutions."

The author has long-standing experience in tribology, especially in micro- and nanotribology. Her work is on the global challenges for humankind and how humankind can address them with sustainable, disruptive technologies, accessing and providing human knowledge and educating future generations. She received her formal science and engineering education in Europe, spent some postdoctoral research time at the physics department of the University of California in Santa Barbara and has been living and working in Southeast Asia since 2008. With a team that consists of architects, designers, engineers, biologists, artists, economists, and a veterinary scientist they learn from virgin forest ecosystems and from each other, jointly developing and refining new synergistic approaches, blending Western and Eastern ways of thinking and perceiving the world and current challenges [30].

The results of the knowledge integration are presented below and in Tables 2 and 3.

Table 2 Components of ecotribological systems: Inspiring publications

Paper title	Category	Keywords and concepts of interest for ecotribology
Autonomic composite hydrogels by reactive printing: materials and oscillatory response [56]	Materials	Less use of metals
Design of polarization-dependent, flexural-torsional deformation in photo-responsive liquid crystalline polymer networks [82]	Materials	Triggered materials
	Structures	Reactive structures
Photoactivatable CRISPR-Cas9 for optogenetic genome editing	Materials	Change of tribological properties with external signals
Tunable shape transformation of freezing liquid water marbles [94]	Structures	Time-limited arrangements
Bioinspired materials that self-shape through programmed microstructures [85]	Structures	Programmed structures
Reconfigurable assemblies of Janus rods in AC electric fields [15]	Structures	Directed assembly of structures
Shape-responsive liquid crystal elastomer bilayers [1]	Structures	Foldable structures
	Surfaces	Structured surfaces
Reconfigurable and actuating structures from soft materials [40]	Agents	Temporal changes of properties
Fluid-driven motion of passive cilia enables the layer to expel sticky particles [89]	Agents	Changes of properties in the triboprocess

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Table 3 Aspects of efficient ecotribological systems, their importance, and examples of how these goals are achieved in living nature

Main aspects		Negative impact on environment	Examples from living nature
Raw materials		High (mining)	Few different chemical elements are used in organisms. The human body for example consists of mainly six chemical elements: 65 % of its mass is Oxygen, 18 % Carbon, 10 % Hydrogen, 3 % Nitrogen, 1.5 % Calcium, and 1.2 % Phosphorus. Of all other chemical elements human bodies contain 0.2 % or less.
	Harmful emissions	High (pollution)	Few
	Water consumption	High (global challenge 2) [42]	Drinking, transport of seeds, living environment (for fish and others)
	Waste water	High (planetary boundaries) [74, 84]	Full of food and fertilizer for others
	Exploitation of resources		In most cases closed circles
	Accessory material		Rarely
	Waste		Rarely
Material transport	Harmful emissions	High	In soil, in air, by water, on animals
	Energy consumption		In living nature, rarely material transport takes place for the production of products. Most is locally harvested and free.
Production using materials			Few base materials with slight chemical variations and amazing structure-function relationships, often structure rather than material causing the respective functions
	Accessory materials		Very rarely, and if used, they are recycled and reused internally
	Harmful emissions		Oxygen was once the toxic gas produced by plants—the web of life adapted and now this gas is important for survival in most organisms—opportunistic approaches in living nature are omnipresent
	Energy consumption		Low
	Solid product waste		Urine and faeces are used as food or fertilizer by other organisms, as are plant shells and nutcases, and other equivalent materials

(continued)

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Table 3 (continued)

Main aspects		Negative impact on environment	Examples from living nature
	Special waste		Food or fertilizer
	Recycling		Omnipresent recycling on all levels
	Liquid product waste		Fertilizer
	Water consumption		Low
	Wastewater		Urine—fertilizer
Product transport	Energy consumption	High	By air and water, free
			Seed transport
			Migrations
			Homing of fish such as salmon and turtles when reproducing
	Harmful emissions		Little, some natural gases (sometimes toxic) emitted from plants and animals
Usage	Harmful emissions		Sometimes—like when the first archaic plants released oxygen—killing nearly all the other organisms on Earth—with time, new organisms arose that actually vitally need oxygen
	Energy consumption		Low, but not the factor that organisms are optimized for [20]
	Packing waste		Biodegradable (fruit peel, nut shells)
Disposal	Combustion		Some organisms need burnt ground to thrive (e.g., fire beetles, [77])
	Recycling		Omnipresent, dead organisms, and waste of organisms are used as food or fertilizer
	Re-usage		Diatom frustules, hermit crab shell
	Utilization		Remnants of certain animals are used as building materials in certain animals (e.g., hermit crabs) or as shelter
	Dumping ground		Limestone hills (remnants from corals), coal deposits, white cliffs of Dover (coccolithophorid shells), etc.

Main aspects from [10]

In the category "Materials", printed autonomic hydrogels with swell/deswell behavior depending on external conditions could potentially be used as valves, actuators, delivery units, or micromachine material [56] and thereby result in less use of metals in machines and devices. Patterned films that twist and fold in response to temperature changes, made from shape-responsive liquid crystal elastomer bilayers [1] could, for example, manage lubricant supply and leakage, and provide valuable progress to the categories “Structures” and “Surfaces”. Changes in lubricant quality with time can be buffered by reconfigurable machine material, switching the demands from rather illusory lubricants that never age to the development of machine parts that react to the quality of the lubricant. In this way, the same tribosystem could also be used in various environments (such as moderate zone, the tropics, the arctic) with specific lubricants tailored for the local needs, without having to change machine components or materials (inspiration from [40]). Fluid-driven motion of passive hairs that enable expelling of sticky particles [89] could potentially help in removal of wear particles and prevent unwanted layer formation during the triboprocess (category “Agents” in Table 3). The work by Smith and coworkers on polarization controlled flexural–torsional deformations in materials with complex geometry, boundary conditions, and loading conditions can give valuable input regarding the management of tribological issues in morphing structures (e.g., structures that can turn on or off enhanced mechanical functions like elastic instabilities from bistable arches) or in soft robotics [82]. Zhang and coworkers [94] experimented with coating small amounts of water with nanoparticles of varying hydrophobicity and the resulting shape transitions during freezing and remelting cycles. Inspired by this approach, the development of fast and easy production ways for tailor-shaped particles for tribological applications can be envisaged (e.g., for standardized test or in managing freezing on windshields of cars and airplanes). Rikken and coworkers [73] review the manipulation of micro- and nanostructure motion with magnetic fields. This opens exciting opportunities to align nanoparticles and/or to induce shape changes that make them anisotropic, resulting in interesting applications for tailored reversible tribological properties (e.g., higher or lower friction coefficient depending on specific demands) and also new in situ tracking methods based on confocal microscopy and dynamic light scattering that allow for real-time measurement of the motion of nanostructures. Anisotropy is widely represented in biological materials, but still not well developed in current technological devices. Especially hard–soft transitions pose problems. The work by Chaudhary and coworkers [15], inspired by Glotzer and Solomon [44], deals with microscale particles that assemble reconfiguably in AC electric fields (tunable patch type, size, and location) and that could become the “atoms” and “molecules” of tomorrow’s materials.

Just recently, Nihongaki and coworkers reported in the scientific journal Nature Biotechnology about their development of gene switches that are activated by light. In this way, precise external signals can control which genes are active and which not. The group aims to expand the work to different colors activating different genes [64]. Thinking such approaches further one might envision programmable materials that can be controlled by external signals. One potential application in tribology might be tunable surface roughness of tires that correlates with the roughness of the ground the vehicle is navigating on, resulting in different tire properties on wet streets at the onset of rain (when due to dissolved fuel components the risk of hurling is largest) and on stony roads where different tire properties would be favorable to ensure the safety of the device.

3.2 Goals of Efficient Ecotribology

The goals of effective ecotribological systems are in the production of the raw materials, in their transport and subsequent product production, in their usage and finally, in their disposal (Fig. 2, [10]). These goals are located in three main areas: production (agents, machine components, systems), reaction (agents, products, direct effects of waste agents) and the life cycle of products (impact on the environment during application and during degradation). Minimum contamination and impact on the environment combined with economical feasibility shall be one of the major goals and aspects of ecotribology (Table 3).

Many of the major challenges that humankind is currently facing are based on our current unsustainable ways of doing engineering, business, and marketing. Pollution, the piling waste problem and the new major water shortages we are

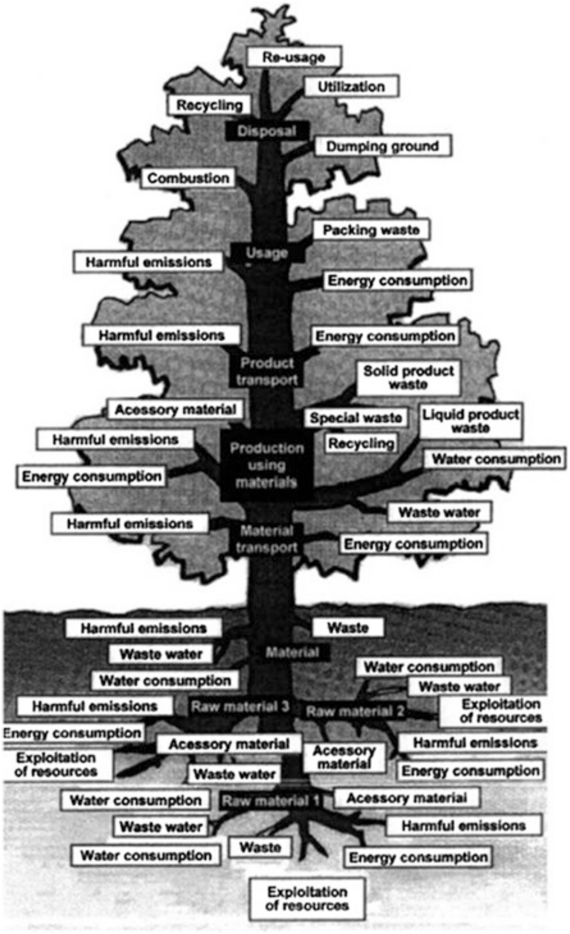

Fig. 2 Eco-Balance tree. Image © Elsevier [10]. Image reused with permission

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facing are all relatively new problems: many of them were initiated by the start of the industrial revolution, at the end of the eighteenth century, when new manufacturing processes enabled the transition from handmade to machine-made products. At this turning point in history, major economic and social changes took place, and production and use of machines, mining methods, and modes of transportation drastically changed. With the industrial revolution, metals, fossil fuels, and concrete started to gain in importance, leading to the engineering-related problems we are facing now.

During the last few hundreds of years, it increasingly turned out that the continuously increasing usage of these materials is unsustainable and needs to be addressed rather sooner than later with novel, potentially disruptive ways of doing engineering, providing similar quality of life, but not at the expense of the biosphere.

New ways of teaching, education, resource management, engineering, economy, etc. might provide the intellectual background and proactive groups of people to deeply think about current problems, develop potential ways to address them, and work on the realizations of solutions.

However, we should not try to just superficially implement strategies such as sustainability and recycling in our new approach. This does not work. A new, disruptive, sustainable approach to engineering, and, in tribology, sound ecotribology need to result from the new complex system we create, as an emergent property; such as collaboration emerges in economies, although all the actors are just concentrating on their own benefit. This kind of emerging sustainability, emerging resource cycling might be a viable solution to current problems.

There is one proven sustainable system that deals with resources, transport, production, use, and disposal of huge masses: living nature. By learning from living nature we might develop ways to improve the current status of the biosphere. Nature can teach us deep principles and viable approaches, and also how not to do things. Additionally to living nature, people and their engineering have the marvelous power to choose their materials. Organisms cannot easily change the materials they use, e.g., for building up their skeletons. Some are stuck with exotic materials such as the mineral celestite (Strontium sulfate), as is the case for the marine organisms with the name Acantharia (Sect. 4.3.1, [28]). They cannot simply switch to another material. People, however, in their technological attempts, can.

The oil dependency of our industrialized nations is still very high: T.C.M. Gupta from Lube World Holdings in Kuala Lumpur Malaysia mentioned in his keynote address at the Malaysian International Tribology Conference 2013 the oil consumption by end use in the energy sector: electric power 3 % (3 % oil dependent), residential & commercial, 6 % (21 % oil dependent), industrial 24 % (43 % oil dependent), and transportation 67 % (66 % oil dependent). In organisms, on the other hand, material transport and product transport are performed without reliance on fossil fuels (apart from the interesting species of oil consuming microbes, see [13]). Organisms only use local resources.

Goals of efficient ecotribology can be achieved by learning from nature. Bioinspired transport in ecotribology is addressed below, for further examples, see

Sect. 4. If we could start to develop engineering approaches that would help us departing from the transport intensive way we are currently using, major energy savings would result, and benefits for the whole biosphere. One potential approach is to emulate the local resource management approach of living nature, and to increase the use of 3D printers using only a couple of materials (similar to living nature), slightly chemically varied (this could potentially be done by the end user?!), resulting in structurally elaborate functional prints (for various applications). The base materials for the 3D printers of course need to be produced and delivered, but since most people in settlements would use similar or the same materials, whole new ways of transport, storage, maintenance, etc. could be envisaged—similar to current water and electricity supplies. Perhaps even local resources can be the major materials of choice, strengthening local markets, materials, and people. 3D printing is a booming technology, allowing for rapid prototyping of complex structures and also for printing of chemical molecules and tissues with a commercially available 3D printing platform: We have already started to initiate chemical reactions by printing reagents directly into a 3D reactionware matrix, and the future might bring printing capabilities for whole organs or machines, from basic ingredients, simple base materials, in our homes [54, 86].

3.3 Optimization Levers in Ecotribology

Inspired by the four optimization levers in tribology suggested by Scherge and Dienwiebel [80] and by the eco-balance tree suggested by Bartz [10] (Fig. 2) we propose focusing on the following in the development of a sustainable ecotribology concept: material selection, finishing, additives, and running-in need to be optimized with regard to the used materials, structures, and processes. Material transport, production using materials, product transport, usage, and finally disposal need to be tailored to prevent further exploitation of resources and negative impact on the environment. Biomimetics can also here give valuable inspiration. Plants, animals, and microorganisms utilize metals in completely different ways than humans (see Sect. 4). Exquisite tribological properties are achieved via water-based chemistry in a state of dynamic nonequilibrium, subject to limits and boundary conditions. As tribological contacts are required to operate under greater tolerances and more extreme conditions than organisms, only principle transfer is possible and advisable in biomimetic tribology, not copying.

"Conventional technological lubricants are uniform chemical compounds achieving specific results regarding the physics of the tribosystem. Biological lubricants are mainly water-based, and in many cases the lubricant chemically attaches to the surface (such as in the lubricant layers reported for synovial joints, the lung, or the eye). Current manmade lubricants are mainly oil based. One reason for this is the thermal instability of water-based lubricants at elevated temperatures. One promising area for bioinspired water-based lubricants are ceramic MEMS that work at ambient conditions, with the lubricants chemically attaching to the surface, building monomolecular lubricant layers [90]" [26, 27].

3.4 Challenges for Efficient Ecotribology

More often than not, ecological and economical requirements do not overlap too much. It is the art of good ecotribology to establish a balance that allows this field to thrive. Especially, when collaborating with huge companies (international corporations such as big oil firms) the visions and mission gaps between the various stakeholders might seem unbridgeable. Corporations have goals and underlie certain constraints that arise from their complex structure. These goals differ from goals of society, and from goals of research. Value-based science is a complicated field, since besides research and development ethics, society and politics are important stakeholders [2, 3]. As Gebeshuber [30] pointed out in "Value based science: what we can learn from micro- and nanotribology", tribology can provide first interesting solutions in this regard. Tribology has always been about properly managing fuel consumption, wear and tear, and optimizing machines, devices, and lubricants. One might even go as far (as stated by Prof. Franek, Scientific Director of the Austrian Center of Competence for Tribology) and say that tribology is inherently green.

The development in tribology regarding policies and research foci is promising: being aware of the damage that has been done with engineering that mainly ignored the environment and just focused on technological improvements (faster, cheaper, smaller, etc.), current funding bodies and tribology research institutions, groups and single researchers and thinkers increasingly incorporate ecotribology thought in their approaches.

Ecological requirements on technological developments need to be put in a concise perspective. We are too much rooted in the present with our regulations and policies. Here, some inspiration could come from indigenous peoples who in their actions think about the seventh generation after them: The Great Law of the Six Nations of the Iroquois, a northeast Native American confederacy, requires that every deliberation considers the impact of any of its decisions on the next seven generations [52]. Indeed, one of the global challenges identified by the Millennium Project is exactly in this realm: Global Challenge 5 deals with the relationship of policymaking and the sensitivity to long-term perspectives: "How can decision-making be enhanced by integrating improved global foresight during unprecedented accelerating change?" [43]. Short work contracts, short research projects, increased frequency of switching jobs, low identification with major goals, and low feeling of being responsible contributes to challenge 5, and need to be properly addressed to go beyond selfish, short-term economic interests. In this respect, the reader might be interested in Berne's conversations with nanoscientists. Berne argues that scientists who are trying to catch "the wave" of nanotechnology have little motive or opportunity, let alone incentive, for reflection [11, 47].

Short-term thinking increasingly is important and demanded in science and technology. Numbers need to be met, and few researchers have time, capabilities, and support to draft long-term ideas and concepts. Indeed, how policymaking can be made more sensitive to global long-term perspectives is one of the global challenges identified by the Millennium Project [43]. Living nature seems to have implemented various approaches to address long-term perspectives, written in the DNA of living beings [81].

3.5 *Prospects of Efficient Ecotribology*

Given the huge amount of papers that are published every year, with many of them neither being read nor cited [48], we need a system that allows everyone, including key stakeholders such as industry, fellow scientists (from the same and other fields), and the general public access to research results [34]. Open Access publications are a start, but expensive. Policies and standards and regulations are important in tribology, especially for product and agent development. The policy makers need to stay informed about potentially hazardous outcomes of research and development, especially in multidisciplinary and emerging fields. The Millennium Project goes even further and demands a knowledge system that ensures sensitivity of policymaking to global long-term perspectives via the establishment of collective intelligence systems that provides continuity from one administration to the next and assists to cope with accelerating knowledge expansions, complexities, and interdependencies while securing public agreement about necessary changes [42]. Glenn and coworkers state that one of the major problems in policymaking are incoherent policies across countries. A related view from the online resources (http://www.millennium-project.org/millennium/Global_Challenges/chall-05.html) of the Millennium Project is: "Leaders should make these new systems as transparent and participatory as possible to include and increase the public's intelligence and resilience. As a result, more future-oriented and global-minded voters might elect leaders who are sensitive to global long-term perspectives. … Universities should fund the convergence of disciplines, teach futures research and synthesis as well as analysis, and produce generalists in addition to specialists." A tree of knowledge, that is accessible by all, and where connections and interdependencies can easily be visualized, would be a first approach to this set of challenges. Gebeshuber and Majlis proposed such an approach in their publication on new ways of scientific publishing and accessing human knowledge inspired by transdisciplinary approaches in tribology [34]. This would help researchers, policy makers and the general public to connect, collaborate, and communicate in order to facilitate the sharing of their knowledge.

Tribology funding bodies and policies increasingly incorporate ecotribology thought in their approaches, yielding promising prospects departing from singular monetary considerations toward responsible actions for the current and future generations.

3.5.1 Three Gaps Toward Sustainability

Inspired by the three-gaps theory that our group introduced in 2009 for inventors, innovators, and investors [35], a three-gaps theory for the path of tribology toward sustainability is proposed (Fig. 3). Successful bridging of these three gaps provides a potential path for successful ecotribology, contributing to propel society toward sustainability.

The three-gaps theory for ecotribology summarizes issues that need to be identified and addressed successfully for the establishment of successful ecotribology. The first gap is between the world of ideas and conventional tribology. Generally, innovation, disruptive ideas, and people who realize the potential of ideas overcome this gap (which acts as *push* in a push–pull theory approach, [96]). In conventional tribology, markets, individuals, and know-how are important. The second gap on the path toward successful ecotribology is to leave the focus on markets, and realize and appreciate the issues that arise for society due to global challenges. Instead of *know-how*, *know-why* becomes important. The effects of tribology are viewed with a broader scope, especially regarding their potential (in combination with other approaches) to successfully address our most pressing problems. The third gap is between identifying global challenges and realizing that also ecotribology is necessary to successfully address some of these challenges and subsequent development and implementation of successful ecotribology. In this way, needs of all life (not just selected human individuals, or countries, or societies, or corporations) are fulfilled and are the main issues of focus. Successful ecotribology is based on profound understanding. Various problems and issues need to be overcome when bridging this gap.

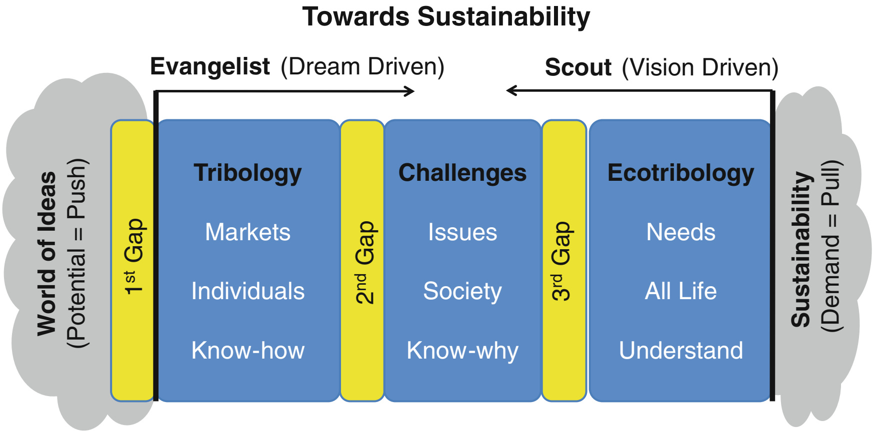

Fig. 3 Three-gaps theory for ecotribology. To propel tribology toward sustainability, three gaps need to be overcome: the one between the world of ideas and conventional tribology, the one between conventional tribology (practice, education) and the most pressing problems we are currently facing, as human societies and as all life of Earth, and the gap between the global challenges and ecotribology that is beneficial for the whole biosphere

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Two specific personalities may arise in such a scenario: dream-driven *evangelists* and vision-driven *scouts*. The idea of scouts and evangelists comes from the classic 2007 paper by Hansen and Birkinshaw in the Harvard Business Review [49].

Ecotribology might be more expensive than conventional tribology when viewed with a narrow, economically oriented focus. In a wider focus, it is necessary—the ultimate goal is sustainability.

3.6 Current Efforts in Ecotribology Exemplified by the World Tribology Congress

International conferences are important for various reasons. First, new trends and developments are treated, and researchers have the possibility to listen to visionaries from their field and related fields, widening their horizons, thoughts, and fields of interest. Activities at conferences, such as personal discussion, entering scientific and technological networks, establishing contacts with industry and researchers alike pave the way for an even more successful career for young and established tribologists.

The World Tribology Congress takes place every 4 years. In 2013 it was in Italy while in 2009 it was in Japan. Ecotribology tracks have been organized at both recent World Tribology Congress events, in 2009 (main organizer: Prof. Shinya Sasaki from Tokyo University of Science, Japan) and 2013 (main organizers: Prof. Ille C. Gebeshuber, Austrian Center of Competence for Tribology, National University of Malaysia and Vienna University of Technology, and Prof. Jianbin Luo, Tsinghua University, China, and Director of the State Key Laboratory of Tribology).

Two plenary talks at the Ecotribology Track of the World Tribology Congress 2009 set the stage for the new and exciting field: Mr. Christopher Flaivin, the president of the Worldwatch Institute, USA, talked about low-carbon economy and Mr. Masatami Takimoto from Toyota Motor. Co., Japan talked about Toyota's initiatives for realizing sustainable mobility.

The keynote speech was by Wilfried J. Bartz, on environmentally acceptable tribological practices. Invited speakers talked about additive performance in bio-based versus paraffinic base oils (Girma Biresaw), new ecological technology for heavy-loaded machine elements (Remigiusz Michalczewski), trends in environmental tribology (Stephen M. Hsu), improving the environmental protection and the economy of i.c. engines with new type of additive (J. Fodor), ecotribology for increasing the efficient use of energy and minimizing environmental impact (Shinya Sasaki), the development of high performance shaft seal "leaf seal" in industrial turbines (Hidekazu Uehara), mixed lubrication analysis of vane sliding surface in rotary compressor mechanisms—influences of flexible structure at surface end of vane slot (Yasutaka Ito) and development of a human-friendly, renewable resource-based metalworking fluid technology, and its impact on sustainable manufacturing (Jake W. Pajak). Interesting to note is the balance between speakers from the industry and speakers from universities and research institutions and the broad approach to the field—this provides a very good basis for something that still needs to be defined properly, such as the new and emerging field of ecotribology.

The Ecotribology Track at the WTC2013 in Torino had five sessions: tribology for energy conservation (with the keynotes on green tribology at sea at Robert J.K. Wood and MEMS/NEMS and BioMEMS/BioNEMS materials and devices and biomimetics by Bharat Bhushan), environmentally friendly tribology, environmentally compatible lubricants, tribology for life—green tribology (with a surprise talk on sustainability by Prof. Satish V. Kailas from the Indian Institute of Science, the premier Indian tertiary education institution), and a panel discussion on ecotribology with an impulse talk [37] on ecotribology development, prospects, and challenges by the author of this chapter. Jianbin Luo, Zygmunt Rymuza, Ali Erdemir, Shi-wei Zang (who coined the term “Green Tribology”), Ille C. Gebeshuber—the author of this chapter, and the artist and ecologist Sigrid Zobl comprised the panel, moderated by Oliver Futterknecht. The session highlighted the importance of ecotribology across fields (ecology, tribology, economy, policy makers, etc.) and of incentives, also from the political side.

4 Sustainable Ecotribological Systems: Best Practice from Living Nature

This part of the chapter deals with inspiration from living nature for the development of successful ecotribology. Rationale for looking at organisms and ecosystems for inspiration is the following: organisms need to cope with issues related to friction, adhesion, lubrication, and wear. They have developed a sustainable system integrating various interesting approaches to tribological problems, such as lubrication of the eye and the hip, protection of inner linings in pregnant women, optimization of skin properties on finger tips (people can hold onto things, even with wet hands), and many more. In the subsections of this section, the inspiring aspects from living nature are sorted related to materials (exemplified by metals), structures (exemplified by structural colors with optimized tribological properties), and processes (exemplified by biomineralized structures with optimized tribological properties) and transferred to ecotribology.

4.1 Materials

Traditionally, metals are of high importance in engineering. In living nature, this is not the case. Apart from biomineralized structures (see Sect. 4.3) organisms only use metals when they are chemically necessary, for example, as the center atom of chlorophyll, Magnesium, and as the center atom of hemoglobin, Iron. Mechanical

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strength, structural support, and further functional properties in organisms are provided rather by highly functional structures of benign materials than by metals. Until mankind is with its technology at such a high stage, metals will still be of utmost importance in tribology.

Heavy metals in the soil and in wastewater pose a threat to human life and cause significant environmental problems. Some microorganisms and plants, however, have the ability to accumulate high amounts of metals in their bodies, some in such high amounts that they can be used for mining (biomining = mining with organisms). Biomining denotes the use of microorganisms and plants (phytomining, see Sect. 4.1.2) to aid the extraction and recovery of metals from ores and further metal-including materials such as electronics waste. The rare and specific cases of metal-accumulating organisms may serve here as inspiration for the potential development of an alternative, less environmentally damaging way to mine for metals for applications in tribology. This section investigates plants and microorganisms that accumulate metals, and that might be inspiration for alternative ways to obtain metallic resources.

Biomining with plants, phytomining, is less profitable than biomining with bacteria. However, this technology has found its niches, and especially in the production of nanoparticles with controlled shape and size, plants are of increasing interest for research and development [57]. Biomimetic resource management via mining with organisms provides innovative ways of interpreting waste, waste effluents, and pollutants as raw materials for research and industry, inspired by materials, structures, and processes in living nature [55].

4.1.1 Biomining with Bacteria

Mining with bacteria is arguably more environmentally friendly, more efficient, and cheaper than conventional mining [55, 70]. In conventional mining, metals are melted from ores in blast furnaces; poisonous sulfur gases, fine dust, and greenhouse gases need to be dealt with. In biomining with bacteria, the rocks and ores are finely grounded and treated with sulfuric acid (the rock-eating bacteria need acidic conditions). This allows the bacteria that are already in the material to grow at fast pace, and to enzymatically alter the oxidation state of the metals, gaining metabolic energy. Rock-eating bacteria feed by decomposing ores, metal containing waste, heavy metal loaded industrial effluents and finely ground mining waste, and rocks with metal content too low for conventional mining, leaving acidic fluids with high metal content from which the metals are subsequently gained via electrical processes.

Biomining with bacteria is well established in various countries: in South Africa, Canada, Australia, Chile, India, and China about 25 % of the Copper and 10 % of the Gold are produced with this method (status: 2015). Further metals that are mined with bacteria comprise Zinc, Nickel, Cobalt, Silver, Uranium, Indium, Germanium, Molybdenum, Palladium, and Lead.

4.1.2 Mining with Plants for Bulk Metals

Contaminated soil and contaminated wastewaters are the result of common manufacturing processes around the world. Plants (such as the sunflower plant [59], Fig. 4) and microorganisms such as bacteria, fungi, algae, and yeast can accumulate heavy metals and safely remove pollutants from waterbodies and the soil. In bioremediation approaches a contaminated environment is biotransformed back to its original pristine condition, with the help of organisms. High accumulation capacity can even be used for the enrichment or recycling of valuable metals. Bioremediation with plants involves minimal site destruction and is aesthetically favorable. Some plants even hyperaccumulate metals [4], i.e., they accumulate extraordinary high amounts of metals that are far in excess of the levels found in the majority of other species growing in the same location, without suffering phytotoxic effects.

Various plants mine the soil and the waterbodies in ways that are contrary to conventional human mining approaches. With their roots they take up metals from the ground, and accumulate them in their bodies. In some cases, various percents of the dry body mass of the plants are metal. When the metal is extracted and concentrated in the plant tissue, the plants are harvested, dried, ground, and burnt as

Fig. 4 The sunflower plant *Helianthus annuus* can be used in a new way of mining metals: phytomining—mining with plants. Photo by Kurt Jansson. Licensed under the creative commons attribution-share alike 2.0 Germany license. Image reproduced with permission

part of the metal extraction process (yielding also thermal energy). After the plant or biomass is burnt to produce bio-ore (small volume plant ash that contains the target metal in high concentrations), it is treated with chemicals to get refined metals. Learning from plants how to mine could potentially revolutionize our way to obtain base materials for our technological devices. In the future, however, a nearly complete replacement of metals by functional structures made from benign materials can be envisaged.

Protection from herbivore attack through feeding deterrence (the plants would taste bad) and from pathogen attack through their toxicity might be the reasons why plants hyperaccumulate metals.

Reeves [72] reports 440 plant hyperaccumulators, 75 % of which hyperaccumulate Nickel. The main characteristics of hyperaccumulators are metal accumulation, metal translocation from roots to shoots, metal enrichment, and metal tolerance.

The Yellowtuft *Alyssum murale* can hyperaccumulate Nickel up to 20 g/kg dry mass, and can reach a biomass of 10 tons per hectare. The Indian Mustard *Brassica juncea* can hyperaccumulate Gold via induced hyperaccumulation, [5] up to 57 mg/kg. Normal Gold concentration in plants is 0.01 mg/kg. Further commonly known hyperaccumulator plants are the Alpine Pennycress *Thlaspi caerulescens* (for Zinc) and the Copper Flowers *Haumaniastrum robertii* and *H. katangense* (for Copper) (Table 4).

Table 4 Hyperaccumulators used in phytomining (selection from 440 species)

Metal	Plant species	Metal concentration (mg/kg d.w.)	Biomass (t/ha)
Cd	Alpine pennycress (*Thlaspi caerulescens caerulescens*)	3000	4
Co	Copper flower (*Haumaniastrum robertii*)	10,200	4
Cu	Copper flower (*Haumaniastrum katangense*)	8356	5
Au[a]	Indian mustard (*Brassica juncea*)	10	20
Pb	Round-leaved pennycress (*Thlaspi rotundifolium*)	8200	4
Mn	*Virotia neurophylla*, flowering plant—IUCN status vulnerable	55,000	30
Ni	*Alyssum bertolonii*, alison species from Europe	13,400	9
	Berkheya coddii, a flowering plant from the daisy family	17,000	22
Tl	Buckler mustard (*Biscutella laevigata*)	4055	4
Zn	Alpine pennycress (*Thlaspi caerulescens calaminare*)	10,000	4

[a] Induced hyperaccumulation

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4.1.3 Mining with Plants for Metallic Nanocrystals

People have argued that phytomining is not as interesting as biomining with bacteria, since the harvest is too small. With the arrival of the age of nanotechnology, and the importance of nanoparticles of specific shapes and sizes, plants and plant-based methods are increasingly important in yielding nanoparticles for research, development, and the market. The price of Gold nanoparticles (with diameters varying between 50–100 nm in one batch) is about 10 times higher than that for Gold in bulk; the price of Gold NPs rises to several thousands of dollars per gram the more defined the size and shape of the Gold nanoparticles need to be. Because of these economic reasons, NP production with plants is viewed with increasing interest.

Biosynthesis of inorganic nanoparticles comprises metallic nanoparticles (NPs), oxide NPs, sulfide NPs, and other typical NPs [57]. Iron oxide nanoparticles (Fe_3O_4-NPs) can be synthesized with Sargassum Algae (*Sargassum muticum*) aqueous extract, Gold nanoparticles are synthesized by the thermophilic bacterium *Geobacillus* sp., the fungus *Verticillium luteoalbum*, and the bacterium *Klebsiella pneumoniae*. The *Lactobacillus* from our yogurts biosynthesizes Silver and Titanium dioxide NPs. The bacterium *E. coli* and the black mold *Aspergillus niger* can produce Silver NPs.

Biosynthesis of Gold, Silver, Platinum, Palladium, silica, alloy, Titanium, zirconia, Selenium, and Tellurium nanoparticles by microbes has already been reported [63]. Also plants extracts such as fruit peel preparations can be used for the plant-mediated biosynthesis of nanoparticles via recycling of metal industrial effluents [57]. See Table 5 for some plant-extract produced NPs.

4.2 Structures

In Sect. 4.1, the way that plants and organisms mine for metals was introduced; a way that is so different to how we are currently doing it with conventional technology. Obtaining metals is important, especially at our current state of affair,

Table 5 Metal nanoparticles produced by plant extracts (selection)

NP material	NP size	Biosynthesizer
Ag	4.6 ± 2 nm	Pu-erh tea (*Camellia sinensis*) leaves [60]
	136 ± 10.09	Oregano (*Origanum vulgare*) leaves [76]
Au	10–30 nm	Damask rose (*Rosa damascena*) flowers [41]
	50 nm mean size	Betel (*Piper betle*) leaves [83]
	25 nm nanorods, 30 nm nanowires	Sugar beet (*Beta vulgaris*) pulp [14]
Pt	2.4 ± 0.8 nm	Oriental Arborvitae Leafytwigs (*Cacumen platycladi*) [95]
Se	60–80 nm	Lemon (*Citrus* sp.) leaves [69]

because various devices and technologies heavily rely on metals for their function. In the course of increasing sustainability of our technologies, however, metals and plastics made from fossil fuels need with time to be replaced with other, more benign materials.

Living nature is facing the same physical problems as our machines and devices. Constructions and devices with moving parts need to cope with gravity, weather conditions, loads, resist wear and tear, and fulfill further tribological requirements. One of the large differences between man-made and natural constructions is the type of materials used and the exquisite tailoring of structures in living nature, often on many levels of hierarchy [23]. The strong relationship between structure and function in organisms is one of the key reasons for the success of biomimetics.

Nachtigall identified general biomimetic principles that can be applied by engineers who are not at all involved in biology [62]. One of these principles is *integration instead of additive construction*. As opposed to the plenitude of different materials currently used in technological approaches, organisms use only a small amount of different materials, however, slightly chemically varied in different applications, and greatly varied structurally.

One example for the realization of the biomimetic principle *structure rather than material* in organisms is the way that colors are produced in some microorganisms and tropical plants [17, 36] as well as in animals such as the peacock, the pigeon, and fish. Minuscule structures on the order of the wavelength of the visible light (in some cases, of the order of the light visible to other animals, such as the ultraviolet light visible for some insects and birds) interact with the light. They do this in similar ways as the tiny water droplets in the air do in the generation of the colors of a rainbow, or a thin film of oil does on water when generating iridescent colors, i.e., colors that change with the viewing angle. The resulting brilliant structural coloration does not bleach, and—in most conditions—does not employ any potentially toxic chemicals but just contains structures from benign materials.

A central aspect of structural colors and structure-based functions in organisms in general that makes them interesting for tribology is their multifunctionality. *Multifunctionality instead of monofunctionality* is a further general biomimetic principle identified by Nachtigall [62]. Structures in and on some beetles, butterfly wings, tropical plants, and microorganisms yield impressive coloration, and also control wetting behavior as well as frictional and adhesion properties [65]. Examples for elaborately structured parts with tribological relevance are the nanostructured hydrated silica hinges and interlocking devices in diatoms (Fig. 5, [31]) that can serve as inspiration for optimized tribology in microelectromechanical systems (MEMS). On an even smaller scale, chemical ice binding properties based on specifically structured molecular adhesives in diatoms come to mind [71].

Diatoms are single-celled algae that biomineralize hydrated silica parts of amazing variety, forms, structures, and functions. There are tens of thousands of different diatom species, all with different morphology. Diatoms range in size from a few micrometers to a couple of millimeters, and some species build chain-like colonies. In the colonies the single cells are mechanically attached to each other by various mechanisms, from adhesives [91] to hinges [31] and nanozippers [87],

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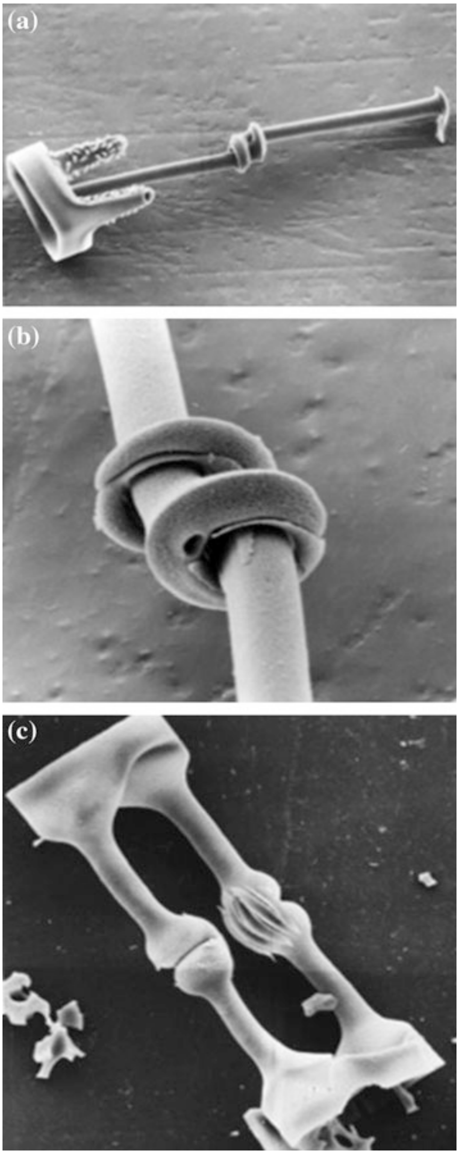

Fig. 5 Diatoms are single-celled algae that biomineralize hydrated silica parts of amazing variety, forms, structures, and functions, interesting for micro- and nanotribologists regarding their optimized tribological properties on the micro- and nanoscale. **a** In the fossil diatom genus *Syndetocystis*, the linking occurs by means of a structure at the center of the valve. One of the diatom valves has been broken and lost. At the apex of each spine is a loop that surrounds the shaft of the other spine. Scale bar 20 µm. **b** A detail of the apex is shown. Scale bar 5 µm. **c** Sibling valves of the diatom *Briggera* with a massive linking structure at either end of the oval valve. Scale bar 20 µm **a** and **b** from [31], **c** from [16]. Permission pending

curiously often permitting movement between cells without detachment [91]. There are several properties of the diatoms that make them interesting regarding MEMS and micro- and nanotribology [25, 38]. For example, they build their exoskeletons during cell division, and do not change the basic frustule after this. Repair does not take place on the hard silica parts. They use hydrated silica as material, and therefore accommodate various functions via structure alone. They are nanostructured, and their optical properties are interesting for nanotechnologists.

4.2.1 Structure Rather Than Material

In this section we give four specific, tribologically interesting examples for the realization of the biomimetic deep principle *structure rather than material* in organisms. Snake scales provide friction reduction; wear protection in iridescent red algae results as by-product (with potentially further functionalities, given the omnipresent multifunctional aspects of biomaterials) in strikingly beautiful iridescent coloration. The tropical butterfly *Morpho* has multifunctional iridescent blue wings. The author encountered *Morpho* butterflies in the virgin rainforest of Costa Rica, when she was doing biomimetics with engineers from the aircraft company, Boeing. The structural black coloration of *Troides* sp., the iridescent coloration of certain Malaysian tropical understory plants, and the calcite tips of marine microorganisms that are exquisitely tailored regarding growth along specific crystallographic axes are further examples from living nature on realizations of the deep principle *structure rather than material* with relevance for ecotribology (Table 6).

Snake scales for friction reduction

Iridescent snake scales might serve as friction reduction structures [24]. Biomimetic inspiration for frictionally optimized structures of household and other appliances might result in beautiful, functional iridescent surfaces. The brilliant strong coloration, especially when limited in bandwidth (i.e., showing over a wide viewing angle only one color, rather than all the colors of the rainbow, see scientific literature on the related structures in the scales of the *Morpho* butterfly and references therein) would be an additional bonus for luxury functional materials.

Wear protection in iridescent algae

The iridescent cuticles of the algae *Iridaea flaccida* and *I. cordata* are tough but flexible outer coverings. They were investigated by Transmission Electron Microscopy [39], and showed multilamination with alternating electron opaque and translucent layers with a total thickness of 0.5–1.6 μm. According to the publication, the electron opaque layers may correspond to protein-rich regions and the electron translucent ones to regions rich in carbohydrates. The cuticle may protect the alga from physical factors such as desiccation, wear, and from predator injury. The authors conclude that it is likely that the iridescence in other foliaceous red algae is caused by a similar structure.

Light and temperature regulation management in black butterflies

Herman and coworkers report in 2011 temperature regulation properties of the black wings of certain butterflies [50]. Butterfly wings need to have a certain temperature so that the animal can fly, but this temperature cannot be too high, because otherwise the proteins and other fragile biomaterials of the organism would disintegrate. Understanding of the contribution of the nanostructures of the black butterfly wings might provide valuable biomimetic inspiration for the development of tailored nanostructured technological materials that would express a passively controlled temperature range. Such materials would find wide use, from building skins to clothing to car surface treatment. The fact that the temperature regulation might substantially originate from the structure rather than the material would allow for property transfer to materials that are already used for the selected applications,

Table 6 Physical mechanisms that yield iridescence in plants, with examples and functions [17]

Physical mechanism	Visual appearance	Example	Function
Thin film interference	Multicolored pointillistic perdium	Slime mold *Diachea leucopoda*	Photoprotection
Multilayer interference	Iridescent blue leaves	Willdenow's spikemoss *Selaginella willdenowii*	Photoprotection
	Iridescent blue leaves	Peacock begonia *Begonia pavonina*	Photoprotection
	Rainbow colored blades	Red alga *Iridaea flaccida*	Wear protection
Diffraction gratings	Blue, green, and yellow iridescent flowers	Flower of an hour *Hibiscus trionum*	Attraction of pollinators
	Flowers iridescent in the UV range (visible for certain insects)	Tulip *Tulipa kolpakowskiana*	Attraction of pollinators
Scattering	Bluish white needles	Blue spruce *Picea pungens*	Preferential scattering of short wavelengths and enhanced reflectance of UV
Photonic crystals	Iridescent blue fruit	Blue quandong *Elaeocarpus angustifolius* syn. *E. grandis*	High visibility in green foliage, contribution to photosynthesis
	White hairs	Edelweiss *Leontopodium nivale* subsp. *alpinum*	UV protection, light guide
	Iridescent metallic blue fruit	*Pollia condensata*	Display and defense
Cholesteric liquid crystals	Iridescence in juvenile leaves	Fern *Danaea nodosa*	Photoprotection

and even allow for transfer to novel, potentially benign materials, for the applications. Imagine regulating the temperature inside cars, inside houses, and inside cooling containers (and containers that keep things warm) simply by passive structures! The manufacturing of the structures might be not cheap, but there would be no maintenance costs, rendering the total costs lower than the conventional, in many cases polluting technology. Controlling the temperature range for certain applications in a certain range would also allow for more specific tailoring of adhesive, lubricants, and additives, excluding the need to develop such tribologically optimized materials for extreme conditions.

Excellent structure-based multifunction of *Morpho* butterfly wings

Morpho butterfly wing scales have received enormous attention from the engineering and biomimetics communities (for review, see [65]). Famous for its iridescent wing scales due to periodic micro- and nanostructures of chitin and air layers, various functions have been identified. Tribologically interesting functions comprise thermal response, selective vapors response due to polarity gradients on the nanoscale (from more nonpolar close to the wing to more polar orthogonally away from the wing, [68]), superhydrophobicity, directional adhesion, and self-cleaning properties.

There are various *Morpho* butterflies, most of which show brilliant blue iridescence. The structures responsible for the multifunctional properties of the butterfly wings vary between species, between male and female butterflies, and with the location of the respective scales on the wings. Christmas-tree like periodic nanostructures act as multilayer reflectors and diffraction gratings, and in combination with ridges in the scales result in wide-angle appearance of the blue coloration. Direction adhesion provides water runoff properties away from the body, and allows the butterfly to fly in rain, without getting its body wet. The contact angle for water is above 150°.

Iridescent blue plants

Structural coloration in animals, plants, and microorganisms mainly appears on the surface of the respective organism. Biological surfaces are the first interfaces in the interaction process between the respective organism and its surrounding environment—another fact that makes them highly interesting for knowledge transfer to tribology.

The iridescent blue lycophyte Willdenow's Spikemoss, *Selaginella willdenowii*, is a common plant in the Malaysian rainforest [58]. It exhibits blue iridescence (Fig. 6; investigation with TEM reveals various layers with less than 100 nm thickness each) on the surface [58]. Figure 6 was taken in the Bukit Wang Recreational Forest in Malaysia, with very long exposure time as to better reveal the blue coloration of the leaves. Seen with the naked eye, the fern is bluish green and seems to glow in semidarkness. The blue coloration is iridescent and changes with the viewing angle. Holding and tilting the leaves results in color change from green to nearly total blue, although not as strong as seen in the long exposure time photograph shown in Fig. 6. It remains for future research to establish the exact functions of this strikingly blue coloration, and its potential inspirational potential for tribology.

Crystal spines in Coccolithophores

Coccolithophores are unicellular planktonic algae with a size of a couple of micrometers. Coccolithophores biomineralize an exoskeleton made of calcitic micro- and nanostructures, with exquisite control of shape, size, and crystal orientation (Fig. 7). Calcite is only one of more than 70 metals and alloys, ceramics, polymers, and composites that are biomineralized by organisms at ambient conditions. See Gebeshuber [28] for a review of biominerals and marine organisms that produce them, including various extensive lists of the materials that are biomineralized, the proteins that aid in biomineralization, and the potential functions of biomineralized structures, including prospects in engineering and medicine.

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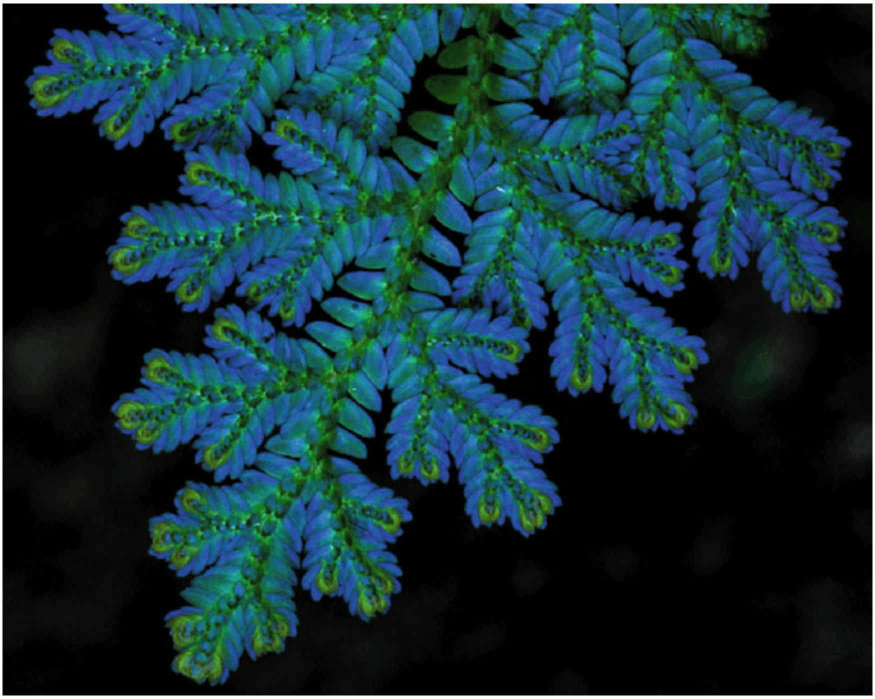

Fig. 6 The iridescent blue lycophyte *Selaginella willdenowii*, a fern ally, is a common plant in the Malaysian rainforest. © Mr. Foozi Saad, IPGM, Malaysia. Image reproduced with permission

The ultrastructure and crystallography of the coccolithophore *Rhabdosphaera clavigera* heterococcoliths was characterized by electron microscopy techniques, including three-dimensional electron tomography, by Young and Henriksen [93]. Five spiral staircases and discrete tip elements made from single crystal {104} calcite rhombohedra units are depicted in Fig. 7. Within the spine core, crystal platelets are hypothesized to serve as a template for nucleation and assembly of the overall structure.

Surface textures are currently an important field in tribology. From the biomineralization in coccolithophores and related organisms novel approaches to textured surfaces will gain inspiration regarding not just the texturing of surfaces of various length scales with potential hierarchical effects, see [23], but also additional synergistic benefit from the control of the shape, size, and crystallographic orientation of the structuring elements.

4.2.2 Tribologically Optimized Microstructures in Organisms

Above, various tribologically interesting microstructures in organisms are presented, and their inspirational potential for ecotribology is outlined. In their classic

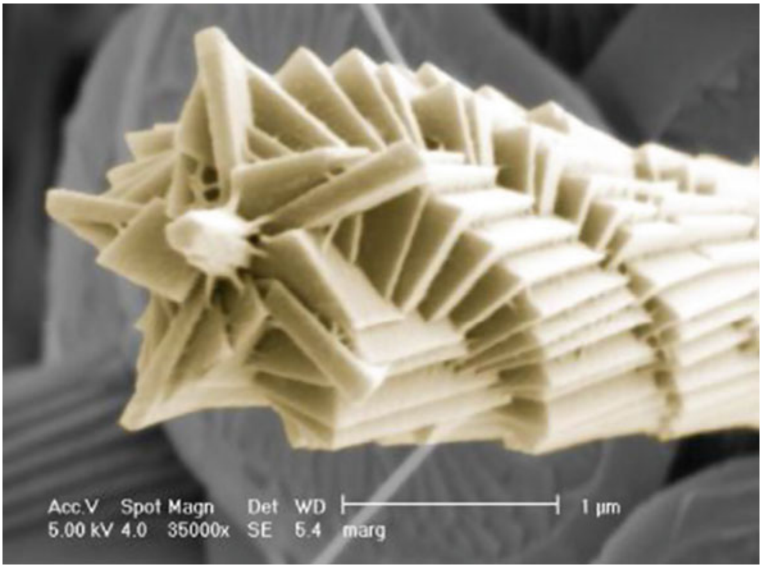

Fig. 7 Spine tip of the microorganism *Rhabdosphaera clavigera*. Material: Calcite, $CaCO_3$. Structure: spiral formed from consistently aligned crystal units with rhombic faces. Process: Biomineralized in cool seawater, with the help of proteins, at ambient conditions. Scale bar 1 µm = 0.001 mm. Image Source: Young and Henriksen [93]. Image reproduced with kind permission of the Mineralogical Society of America

book, Biological micro- and nanotribology: Nature's Solutions, Scherge and Gorb [79] give various further examples. The fast technological progress in nanoscale characterization and production of functional micro- and nanostructures in recent years suggest revisiting the classic book, and developing interesting, potentially disruptive solutions for ecotribology.

4.2.3 Tribologically Optimized Nanostructures in Organisms

Research results such as the finding of a polarity gradient in the single Christmas-tree like nanostructures of the *Morpho* butterfly [68], as well as further nanoscale gradient properties that have been identified in organisms, such as the nanoscale material gradient in adhesive setae of a ladybird beetle [67] promise various additional research findings on such structures in organisms, and increased knowledge about their functionalities and technological ways to produce them, for optimization of tribological properties.

4.2.4 Bridging the Gap: Functionality Across Scales

Micro- and nanotribological investigations are important to establish basic tribological understanding. For transfer of the found principles, processes, etc. to applied tribology, the gaps between the small scales and the macroscale need to be bridged [88]. Bridging the gap between length scales is one specific issue in biomimetics, since more often than not organisms exhibit hierarchical properties, with functionalities at each length scale, and added, synergistic functionalities because of hierarchies [23].

In Sects. 4.1 and 4.2, materials and structures in organisms and potential knowledge transfer to tribology were introduced.

Many of the presented structures are orders of magnitude away from the macroscale: the length scale of their functional units spreads from the micro- and nanoregime to the macroscale: some *Morpho* butterflies have 20 cm wingspan. The different questions asked in the respective studies require scientific investigations at different resolutions. Scale effects need to be addressed when establishing tribological models across scales [12].

Microtribological investigations yield important information concerning wear, surface fractures, the formation of structures between microscopic parts of the tribosystem and their boundaries (tensions, shears, rupture, deformation, etc.). On the nanoscale, molecular properties can be probed. Depending on the questions to answer, investigations on the length scales of surfaces, clusters, and molecules might be necessary.

An interesting and challenging fact about tribology is that it is a systems science. The same holds for biomimetics. Detailed understanding of a whole tribosystem is dependent on understanding of the connections, interdependences, and single functionalities on all length scales of functionalities.

4.3 Processes

The third category in which ecotribology can learn from living nature is in the large and important area of processes. Materials and structures in living nature are produced via completely different approaches than materials and structures currently applied in tribosystems. One intriguing example for the exquisite processes employed in living nature is biomineralization of more than 70 different metals and alloys, ceramics, polymers, and composites by living organisms [61].

4.3.1 Biominerals

Such materials comprise carbonates such as $CaCO_3$ shells in mollusks, phosphates such as hydroxyapatite in bones, oxides such as magnetite Fe_3O_4 in bacteria, sulfates such as celestite $SrSO_4$ in radiolarians, sulfites such as pyrite FeS_2 and greigite

Fe_3S_4 in magnetotactic bacteria, arsenates such as oripiment As_2S_3 in bacteria, native elements such as Gold nanoparticles in yeast, silica $SiO_2 \cdot nH_2O$ in diatoms, halides such as fluorite CaF_2 in fish, and organic minerals such as guanine in fish scales, providing the beautiful fish silver (Table 7, [28]).

Biomineralization is characterized by chemical reactions involving proteins, the creation of perfect crystals, the control of crystal growth and inhibition depending on the crystallographic axis, as well as the production of composite materials with properties that are of high value to engineering.

One of the amazing properties of biomineralization in organisms is that material, structure, and function are strongly correlated.

The combination of minerals, which are usually stiff, brittle, and cheap energywise, with soft and pliable organic materials synergistically results in biominerals with amazing functionalities, such as bone with its seven levels of hierarchy.

4.3.2 Production of Microscopic Tribosystems in Freezing Water

Uncontrolled ice crystal formation inside living cells is dangerous for organisms. Various freeze protection proteins and ice nucleation proteins that promote and control freezing can be found in living cells. Technological applications of these materials are the production of artificial snow, antifreeze agents for aircraft and windshields, and novel, protein-assisted ways to control the feeling of frozen food in the mouth (cf. oral tribology). One example is the use of ice nucleation proteins in water-based ice cream, causing smooth and milky texture, comparable to the high calorie milk-based ice cream.

Various diatoms contain such proteins, and biomineralize their hydrated silica structures in saltwater at subzero temperatures. An intriguing example is the polar diatom *Corethron* [31]. *Corethron* is packed with tribologically interesting rigid parts in relative motion, such as a click-stop mechanism and chiral hooked spines, serving as inspiration for novel 3D MEMS.

4.3.3 Proteins Controlling Biomineralization

Scientists are just beginning to understand the role of proteins in biomineralization [92] and its tremendous potential for the tailor-made production of functional nano-, micro, meso-, and macrostructures with optimized tribological properties [30].

Active roles of proteins in biomineralization comprise inhibition of spontaneous mineral formation from solution (e.g., the protein statherin in the mouth inhibits spontaneous precipitation of Calcium phosphate), inhibition of growth of existing crystals, and responsibility for directing crystal nucleation, phase, morphology, and growth dynamics.

The shape of biomineralized crystals (such as the single crystal teeth of sea urchins) is affected by proteins with specific structures and sequences that adsorb to different faces of the crystal, leading to regulation of shape (crystal faces have

Table 7 Exemplary list of biominerals produced by organisms

Biomineral	Chemical formula	Biomineralizing organism
Carbonates		
Calcite	$CaCO_3$	Molluscs
Strontianite	$SrCO_3$	Snails, microbes, cyanobacteria
Siderite	$FeCO_3$	Bacteria
Phosphates		
Hydroxyapatite	$Ca_5[OH\vert(PO_4)_3]$	Vertebrates (bones, teeth, fish scales), snails (grating tongue)
Whitlockite	$Ca_{18}H_2(Mg,Fe)^{2+}{}_2(PO_4)_{14}$	Dental plaque
Vivianite	$Fe^{3+}{}_2(PO_4)_2 \cdot 8H_2O$	Bacteria
Oxides and hydroxides		
Magnetite	Fe_3O_4	Eubacteria, archaeobacteria, teleosteans, chitons
Amorphous ilmenite	$Fe^{+2}TiO_3$	Foraminifera, snails (grating tongue)
Akaganeite	β-FeOOH	Bacteria
Sulfates		
Celestite	$SrSO_4$	Radiolarians, acantharia, algae, foraminifera, snails (shell)
Jarosite	$KFe^{3+}{}_3(SO_4)_2(OH)_6Z$	Fungi, bacteria
Barite	$BaSO_4$	Bacteria, algae, diatoms, foraminifera, loxedes (gravity receptor), clams
Sulfites		
Pyrite	FeS_2	Magnetotacic bacteria
Galena	PbS	Sulfate reducing bacteria
Greigite	Fe_3S_4	Magnetotactic bacteria
Arsenates		
Oripiment	As_2S_3	Bacteria
Native elements		
Gold	Au nanoparticles	Yeast, sponges, algae
Silver	Ag nanoparticles	Fungi
Uranium	U nanoparticles	Bacteria
Silicates		
Hydrated silica	$SiO_2 \cdot nH_2O$	Radiolarians, diatoms, glass sponges, limpets, mollusks
Halides		
Fluorite	CaF_2	Skeletons, fish skin, mollusk shells
Hieratite	K_2SiF_6	Mammalian gravity receptors
Atacamite	$Cu_2(OH)_3Cl$	Bloodworms
Organic minerals		
Guanine	$C_5H_5N_5O$	Fish, spiders

(continued)

Table 7 (continued)

Biomineral	Chemical formula	Biomineralizing organism
Magnesium oxalate (Glushinskite)	$Mg(C_2O_4)\cdot 2(H_2O)$	Plants
Copper oxalate (Moolooite)	$Cu(C_2O_4)\cdot 0.4H_2O$	Plants, fungi, mammals

Adapted from [28]

different charges and arrangements of atoms so proteins can selectively adsorb). Furthermore, proteins can self-assemble into ordered arrays that guide the formation of organized mineralized structures. Transferred to tribology, such protein-mediated approaches would allow for controlled, tailored growth of tribosystems at ambient conditions, with materials drawn from local resources, and little or no waste.

Common principles in the three main organic structuring and scaffolding polymers, chitin, cellulose, and collagen, are nanofibril formation (1.5–2 nm diameter), ability to self-assemble, production of fibrillar and fiberlike structures with hierarchical organization from the nanolevel up to macrolevels, ability to act as scaffolds and as templates for biomineralization, and the formation of rigid skeletal structures [22].

Certain proteins provide active organic matrices that control the formation of specific mineral structures; others act as catalysts that facilitate the crystallization of certain metal ions [92].

4.4 Knowledge Transfer to Ecotribology

4.4.1 Common Language

Ecotribology is a highly diverse field, with actors from a multitude of areas of specialization, working in basic or applied research, or in industry. It is increasingly harder to identify workforce with the diverse skills demanded from a tribologist.

Due to increased specialization in science and engineering, many people work just in one small aspect of their respective field—this also holds for tribologists. Such specialists increasingly get to know their area better and better but in some cases have no time or think they have no reason to talk to specialists of related but slightly different fields. In the extreme, the specialist languages become too detailed, no joint language can be reached across fields, and writings and oral presentations of authors only reach an audience coming from the same field.

If we are to understand biological tribosystems and develop theoretical models across scales that can fulfill the requirements we demand from models in science and technology, namely, to provide a way to predict the behavior and performance of other, unrelated systems, knowledge transfer between the fields of specialization needs to be ensured. Only in this way, good biomimetic technology is the result, and only properties that are intended to be transferred are indeed transferred.

Functionalities on the nanoscale influence functionalities on the microscale and subsequently on the macroscale. One of the goals in basic tribology research is a unified approach to energy-dissipating systems that encompasses most tribological phenomena.

Three needs can be identified regarding successful development of such a unified approach to energy-dissipating systems: We need a joint language, a joint way of publishing results and joint seminars, workshops, and conferences. Developing these three needs further results in a general concept concerning the future of scientific publications and ordering as well as accessing the knowledge of our time [34].

Currently, over-information in almost any field is a problem. Jack Sandweiss, editor of Physical Review Letters for 25 years, stated in 2009 in an editorial address "*For example, it is currently impossible for anyone to read all of Physical Review Letters or even to casually browse each issue*" [75]. Sandweiss refers to just one single journal!

Gebeshuber and Majlis suggested in 2009 dynamic publications of variable length that use various types of multimedia with adaptive information content. One and the same "paper" would be accessible to readers from various backgrounds and areas of specialization. In case more detailed information is needed, simple clicks on the links would expand the "paper" in the direction(s) wanted. "Recommendation agents" of the future could constrain information and thereby protect users from over-information by making the number of recommendations a function of the user's ability and readiness information intake.

In this way, ecotribology generalists would emerge; people who ensure knowledge transfer from one area of specialization to the other—contributing to a sound foundation to establish a unified approach to energy-dissipating systems across scales.

4.4.2 Biomimetics

Interacting surfaces in relative motion occur in tribology as well as in organisms. Biomimetics, the "Abstraction of good design from Nature" (definition from the Centre of Biomimetics at the University of Reading, UK) can therefore provide valuable developments in ecotribology. Specifically, the field of biomimetics deals with the identification of deep principles in living nature and their transfer to humankind [46]. The German biologist Werner Nachtigall identified ten general biological principles [62]. They can be applied by engineers who are not at all involved in biology, and are: integration instead of additive construction, optimization of the whole instead of maximization of a single component feature, multifunctionality instead of monofunctionality, fine-tuning regarding the environment, energy efficiency, direct and indirect usage of solar energy, limitation in time instead of unnecessary durability, full recycling instead of piling waste, interconnectedness as opposed to linearity and development via trial-and-error processes.

Currently, with nanotechnology as booming new promising field, the sciences have started to converge, with nanobioconvergence as one of the most promising examples. New materials, structures, and processes can arise from this novel approach, perhaps exhibiting some of the multifunctional properties of the inspiring organisms, where various levels of hierarchy (with additional functionality on each level) are so refined. We are hopeful that fully developed ecotribology will also exhibit one of the most important properties ensuring continuity of the biosphere: sustainability.

5 Conclusions and Outlook

Ecotribology is an exciting new field of tribology combining attention to ecological as well as economical aspects. Biomimetic approaches inspired by the oldest sustainable system we know, living nature, might pave the way toward efficient ecotribology, combining ecological and economical interests, and provide a liveable future for all.

Rich chemistry is found within interfaces in sliding contacts and there is a tight connection between chemistry and mechanics. Chemistry is of utmost importance in new ways to deal with resources, materials, structures, and functions. We need to foster the necessary skills to develop programmable materials, we need to slightly but effectively change base materials to obtain certain functions, and we need to establish a base set of materials that, in all sizes and shapes, are not harmful for people and the environment. Shape gets increasingly important, the smaller the particle—the toxicity of nanoparticles paramountly depends on shape, and shape on the nanoscale, can make a certain material either benign, neutral, dangerous, or highly toxic. One possibility to address the toxicity issues on the nanoscale might be to make dangerous and highly toxic nanomaterials fuse together, on demand, via a signal, resulting in harmless larger structures. This might be important for scenarios where nanomaterials leave reaction containers (inside they could very well be used for certain reactions, ensuring rendering them harmless when outside).

Career prospects in ecotribology are soaring, and contributing to the development of successful ecotribology is satisfying on the personal level as well as on societal levels—therefore, it is a highly recommended field for young tribologists to enter.

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Index

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