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Nano-tribology and Materials in MEMS

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Preface

The field of nanotribology has advanced to a great extent thanks to the phenomenal growth of information storage industry. The magnetic hard disks used for recording and retrieving digital data require extremely thin nanolubricant for the protection of the disk from mechanical damages and wear by the slider which flies just above the surface of the disk with flying height only a few nanometer. Even though the slider is designed not to touch the disk, contacts between the slider and the disk are inevitable and hence we require the protection of the disk by the nanolubricant. A similar requirement, at least in length scale, is experienced in microsystems such as micro-electro-mechanical systems (MEMS) where micron-sized components, usually made of Si, are made to move about just like their macro-machine counterparts. Sliding, contact and impact between the components lead to the problems of adhesion, friction and wear. Because of the small length scales involved, the problems of tribology faced in microsystems differ drastically from those of the traditional macro-scale machines. Therefore, it is important to address these issues taking into considerations the materials, micro-fabrication process, lubricants and the lubrication methods.

A symposium titled "Nano-tribology and Related Materials Issues in MEMS" was organized by the Department of Mechanical Engineering, National University of Singapore from 13 to 14 May 2010. A number of invited talks were presented covering the fundamental nanotribology concepts, applications of new materials, surface modifications of Si and polymer substrates and simulations of the friction phenomenon under light load conditions. This book is a collection of the papers that were submitted by the presenters with some additional contributions by the experts in this field. Each chapter has been carefully selected and edited to bring out current practices in the MEMS tribology field with the explicit aim of finding appropriate solutions to the tribological problems faced in MEMS and nano-scale machines.

The editors would like to express their deepest appreciations to the invited and poster presenters of this symposium without whose help this event would not have been a reality. We thank the Dean, Faculty of Engineering and the Head of the Department of Mechanical Engineering, NUS, who provided all the supports needed for the organization of this event. We are also grateful to the Singapore

National Research Foundation (NRF) for the generous research grant (Award no.: NRF-CRP 2-2007-04) to our team which helped to support much of the research works that were presented in this symposium. Finally, we would like to thank the publisher and the authors of the chapters whose relentless effort through the manuscript preparation and editing has resulted in this compilation of very relevant works in the field of nanotribology and materials for MEMS. We earnestly hope that this edited book will positively add to the expanding literature in this field to help in current and future research.

April 2013

Sujeet K. Sinha
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Chapter 2
Biomimetic Inspiration Regarding Nano-Tribology and Materials Issues in MEMS

Ille C. Gebeshuber

Abstract Tribology is omnipresent in living nature. Blinking eyes, synovial joints, white blood cells rolling along the endothelium and the foetus moving in a mother's womb—tribological problems with evolutionary optimized solutions! This chapter introduces biology for tribologists, highlights the benefits of biomimetics (i.e., knowledge transfer from living nature to engineering), first for tribology in general and subsequently specifically for nano-tribology and materials issues in MEMS. The outlook deals with perspectives of green and sustainable nanotribology for a liveable future for all.

Contents

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Introduction

> Producing each of its creations… nature intermingled the harmony of beauty and the harmony of expediency and shaped it into the unique form which is perfect from the point of view of an engineer. (M. Tupolev)

Biomimetics is especially inspiring when it comes to MEMS. This has the reason that in organisms and in MEMS, just very few base materials are used, and variations in the structure are used to achieve certain functionalities. The relationship between structure and function is highly distinct in most biological entities. One prominent example for structure-based approaches at achieving certain functionalities is structural colours. These colours are generated by the structures alone, no chemical dyes are needed (examples: rainbow, thin oil film on water, soap bubble, CD, DVD, certain butterfly wings, iridescent slime moulds, blue tropical understory ferns, …) (Kinoshita [1] Gebeshuber and Lee [2]). The usage of structures rather than material is one of the basic principles of biological systems. Organisms are also excelling at just slightly changing the chemistry and thereby achieving altered functionalities—in this regard out rechnology is just at the beginning with our current material science.

Tribological and material issues prevent successful implementation of 3D MEMS in current technology. Some of these issues can be addressed by improved structures of the MEMS. Conveniently, there is a best practice system in nature where rigid parts on the hundreds of nanometers scale occur in relative motion: diatoms. Diatoms are single celled algae that biomineralize an outer shell of silica [3]. This silica shell is nanostructured, and—for some of the tens of thousands of different diatom species that exist—exhibit hinges and interlocking devices on the micro— and nanoscale [4–6], (Fig. 2.1). Normally, biotribological systems are rather optimized regarding friction than regarding wear. However, and this makes the diatoms so interesting concerning MEMS development (where friction is the major issue), diatoms are optimized regarding wear—one reason for this being that normally, living tissue can be repaired, therefore the focus is rather on friction than on wear, whereas in the case of the diatoms, the shells are built just once and generations of these single celled organisms have to live with them (since at cell division, each daughter cell receives one shell from its parent cell, and biomineralizes the other).

No sign of wear has ever been detected in diatoms (Richard Crawford, personal communication), even when exposed to rough environments or when they were lying in the ground for millions of years, as for example the Eocene fossil diatom *Solium exscuptum* in Fig. 2.1 that was alive 45 millions of years ago.

Nanotribology and MEMS are highly interesting, interdisciplinary research areas. This calls for well educated people who can think deeply and who not only possess book-learnt knowledge, but who can understand and connect knowledge, and construct realities from few, scattered inputs with lots of unknowns. Current education in most cases does not promote such an approach to knowledge. Various

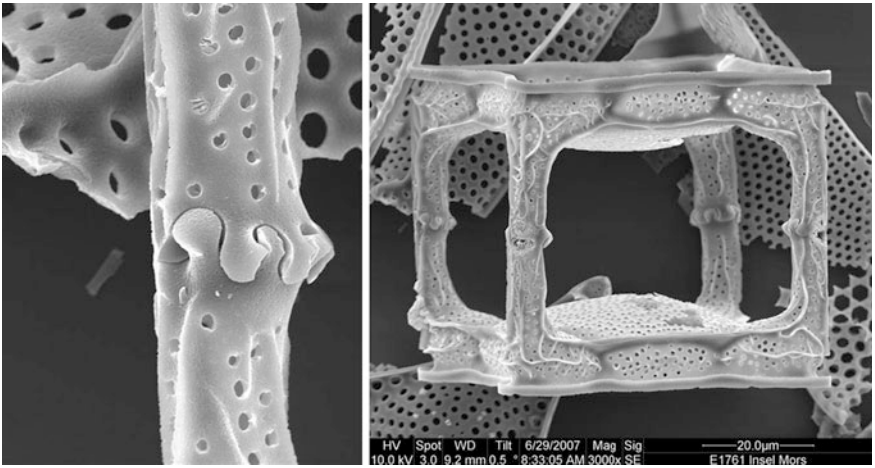

Fig. 2.1 The diatom *Solium exsculptum* lived 45 millions of years ago. This fossil diatom from the island of Mors in Denmark is from the Hustedt Collection in Bremerhaven, Germany, # E1761. It beautifully shows a nanostructured shell, reinforcement ribs, connections and primary mechanical structures. The image on the *left* is a zoom into the most *left* junction in the *right* hand image. Image © F. Hinz, AWI Bremerhaven. Image reproduced with kind permission

undergraduate programs in nanoscience and nanotechnology are underway in many countries, and it remains to be seen if the people produced by these programs are the independent thinkers that are currently needed to propel our society forward towards sustainability [7].

The large degree of interdisciplinarity in nanoscience, in nanotribology and in bioinspired MEMS approaches calls for interdisciplinary scientists who have access to the frameworks of thoughts in more than just one discipline. Concerning nanomaterials engineering, Gebeshuber and Majlis introduced in 2011 a novel concept for innovation [8]. This concept can be translated to nanotribology and MEMS: the basic idea is to apply the 3D method (3D stands for discover, develop and design, Fig. 2.2) to the engineering problem one is currently working on. Ecosystems with high biodiversity such as virgin tropical rainforests are used as treasure box full of ideas and best practices, and the engineers team up with local biologists, designers and materials scientists and spend intense time discussing the problem and watching nature from a functional point of view on rainforest walks. Besides the virgin tropical rainforests, coral reefs can serve as inspirational environment for the nanotribologist, due to their exquisite biodiversity and the high complexity of the interactions (c.f., tribosystem).

This chapter gives an overview of work in our group and of others over the last 10 years in the field of micro— and nanotribology, biomimetics, learning from biology for the tribologists and bioinspired MEMS development.

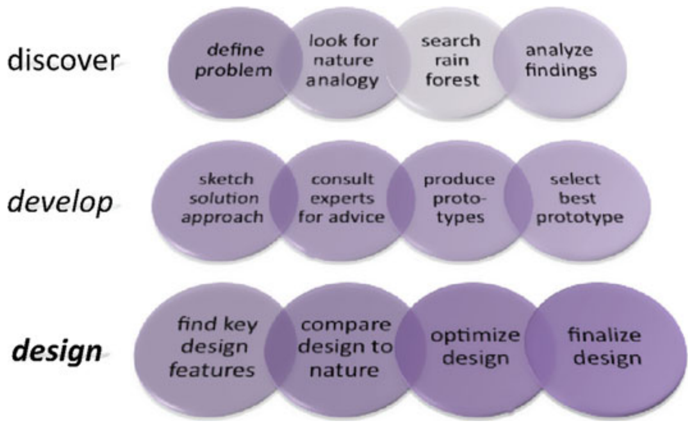

Fig. 2.2 The three pillars in the 3D concept for innovation in nanomaterials engineering [8]. Copyright © 2011 Inderscience Enterprises Ltd. Own image reused with permission; Inderscience retains copyright of the original figure and the article [8]

Biology for Tribologists

It is not easy for tribologists to appreciate the world of biologists. Complicated Latin names for the organisms and highly descriptive style of published work for centuries separated the two fields. Only just recently, collaboration for specialists from the respective fields became increasingly easier. The reason for this change is that tribology as well as biology went through major changes, and additionally, biology and nanotechnology converge on the nanoscale [9]: in both fields, the amount of descriptive knowledge decreases, while the amount of causal knowledge increases, proving a promising area of overlap in terms of ideas, goals, visions, approaches, concepts and language [10], (Fig. 2.3).

This overlap results in an increased number of joint research projects and publications related to biotribology (Fig. 2.4). Starting from 2001, the amount of related papers in the ISI database has increased manifold. Note that 2001 was the publication year of the book “Biological Micro— and Nanotribology: Nature’s Solutions” [11] by Scherge and Gorb.

Normally, engineers and biologists do not see very much overlap in their professions. There are nevertheless various synergies that result from collaborations of these two fields. This has for example been shown in intriguing ways by George de Mestral, the inventor of Velcro (which in fact was inspired by a plant with hooks), by a bioinspired bale-straw screw and by the self-cleaning effects of the lotus leaf found by Barthlott and collaborators (summarized by Gebeshuber and Drack [12]). Biomimetics can happen in two directions, both of which are important and yield new results (Fig. 2.5). In “Biomimetics by Analogy” the tribologist formulates the problem, looks in nature for inspiration, identifies best

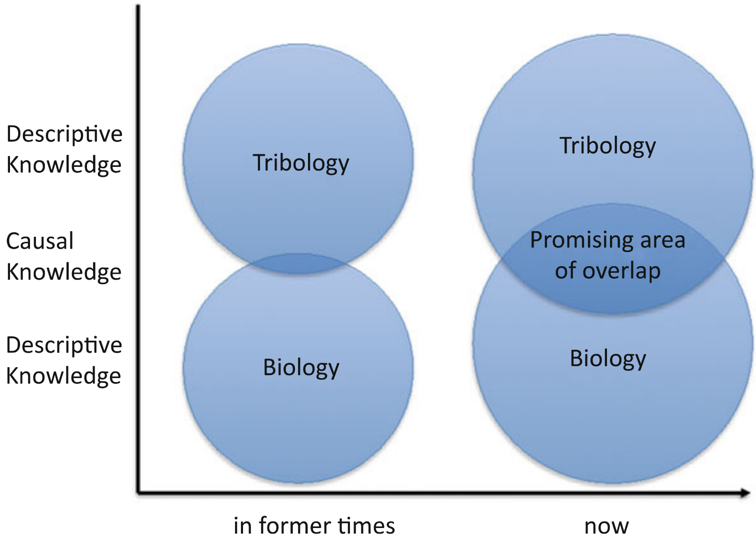

Fig. 2.3 The increasing amount of causal laws in biology generates promising areas of overlap with tribology [10]. © Springer 2011. Own image reused with permission

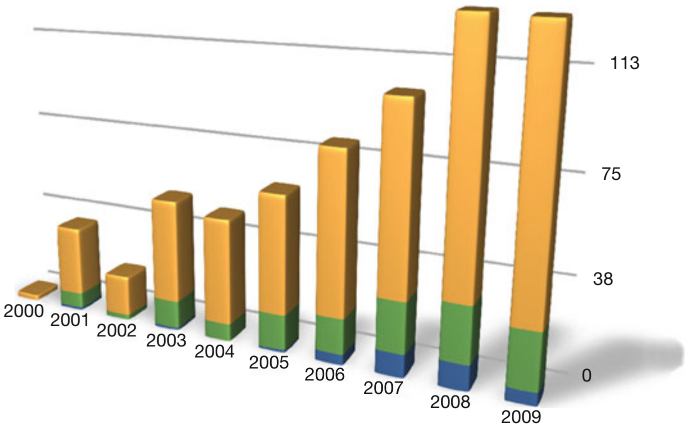

Fig. 2.4 Number of ISI publications on biotribology in the period from 2000 to 2009 (from Gebeshuber and Majlis [34]). *Yellow* bio* and tribolog* in topic, *green* biology* and tribolog' in topic, *blue* biomim* and tribology* in topic. © 2010 W. S. Maney and Son Ltd. Own image reused with permission

practices and their deep principles and transfers them to engineering. In this way, the bale-straw screw was invented [13].

In our increasingly converging society and with the major attempts being undertaken regarding nanotechnology (where all the natural sciences meet), engineers are expected to have basic knowledge in biology. Some engineers went

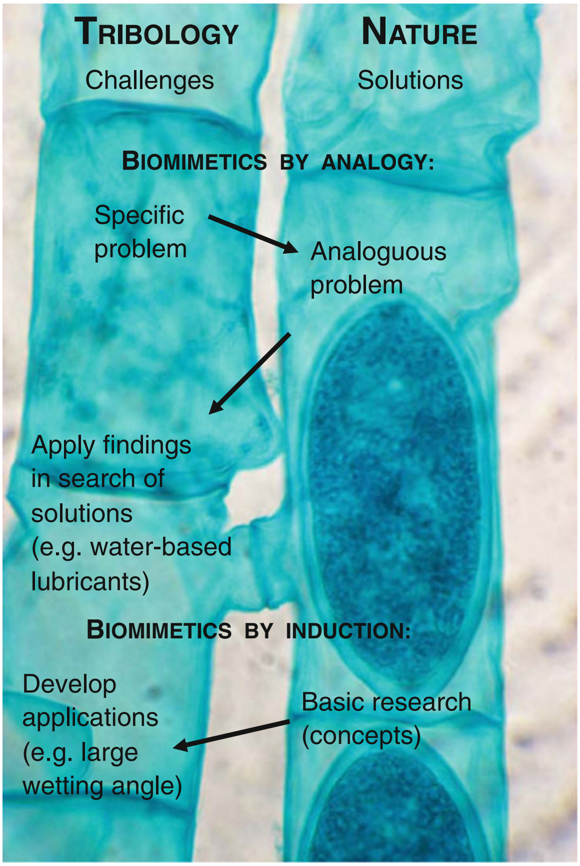

Fig. 2.5 Ways of inspiration by nature for tribologists. *Background image* conjugation in the alga Spirogyra where two originally independent cells form a connection, resulting in exchange of intracellular material, symbolizing fruitful exchange between nature and tribology. © David Polcyn, California State University, San Bernardino. Image reproduced with permission

through a purely technical education, and therefore even lack most basic ideas about biological systems. Arthur T. Johnson, U.S. American professor in a Biological Resources Engineering Department in Maryland, went trough major efforts when writing his book 'Biology for Engineers' [14]. On nearly 1,000 pages he deals with principles from the sciences (physics, chemistry, mathematics and engineering sciences as well as biology), responses of living systems, scaling factors and how to utilize living systems. This book is highly recommended for the beginner-in-biology engineer.

In 2001 Scherge and Gorb's meanwhile classical book on nature's solutions regarding biological micro— and nanotribology appeared—they treat treefrogs, insects, the gecko, and many other organisms with increased or decreased adhesion or friction. Before this date, most of the biotribological literature was concentrated just on a handful of examples from nature, and some decades ago, biotribology solely indicating work related to synovial joints (e.g., hip and knee joints), such as the highly influential work published in Proc. IMechE Part C ([15–17] revisited by Gebeshuber in [18]).

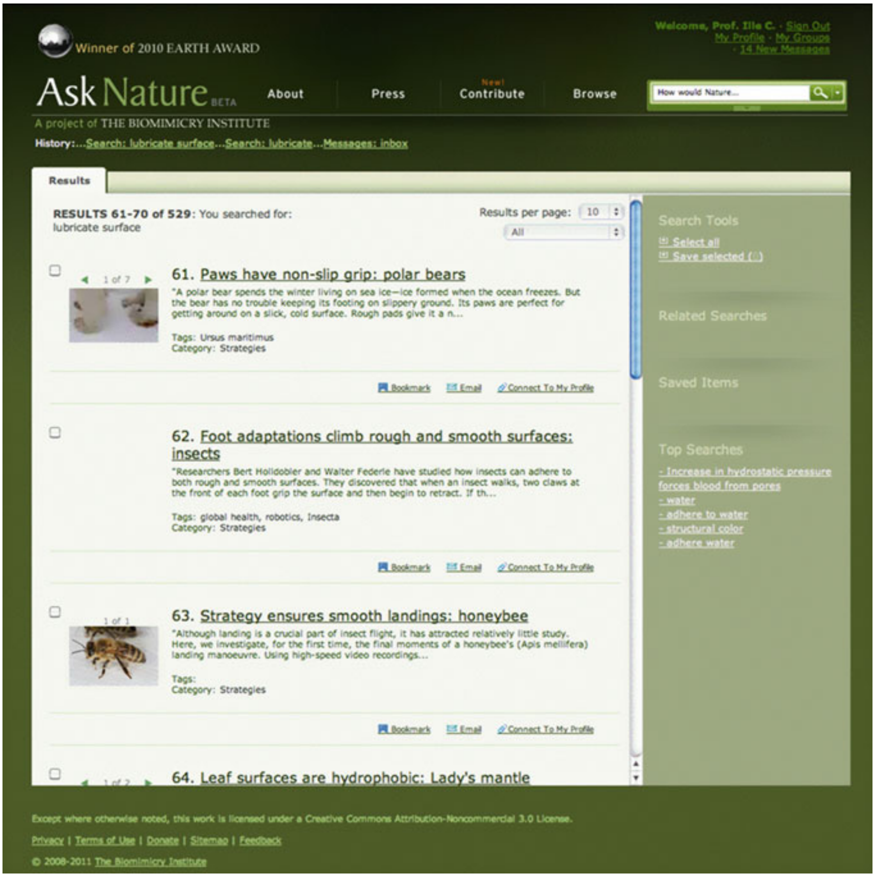

Fig. 2.6 The Ask Nature database from the US American Biomimicry Guild is a helpful tool to start reading into strategies of nature regarding inspiration for biomimetics applications. Tribologists find a plenitude of natural materials, structures and processes that provide input for subsequent sustainable development of biomimetic devices. http://www.asknature.org/

The U.S. American Biomimicry Guild established the Ask Nature Platform, a free web-based application that allows browsing and searching "strategies of nature" (Fig. 2.6). This is an indispensable database for tribologists who want to start to read on biotribological systems or to deepen their knowledge on them (http://www.asknature.org).

One whole section in the book chapter "Biomimetics in Tribology" [9] in a recent a Springer publication on biomimetics [19] is denoted to Johnson's biology for engineers, where the authors predominantly concentrate on biological responses and their possible extrapolation to technical systems. Biology is evolving as new Leitwissenschaft, with more and more causation and natural laws being uncovered. Biomimetics is a field that has the potential to drive major technical advances and that might change the research landscape and the engineering culture dramatically, by the blending of disciplines. Biomimetics might substantially support successful mastering of current tribological challenges concerning friction, adhesion, lubrication and wear in devices and systems from the meter to the nanometer scale. In the introduction of the chapter, the authors highlight the historical background and current developments, then biology for engineers is treated (inspired by Johnson 2009). Subsequently, the biomimicry innovation method that was introduced by the Biomimicry Guild in 2008 is explained. This highly successful method in biomimetics has three steps: Identify function, biologize the question, find nature's best practices and generate product ideas. The method is subsequently applied to identify biological systems, processes and materials that can inspire tribology. The knowledge base used in the analysis is the Ask Nature database from the Biomimcry Guild (http://www.asknature.org/): Major categories from this database comprise 'maintain physical integrity' and 'move or stay put', with various sub-categories such as 'manage structural forces', 'prevent structural failures' and 'attach'. The results of the study are a plenitude of best practices and possible applications (incl. extensive references) concerning mechanical wear, shear, tension, buckling, fatigue, fracture (rupture) and deformation and attachment (permanent and temporary).

Many of the best practice examples in [10] are diatoms. Diatom tribology started in 1999 when the first atomic force microscopy images of living diatoms in ambient conditions were obtained [20].

> Girdle bands can telescope as cells elongate and grow…. The bead-like features on the edges of the girdle bands … are yet to be identified. This is the first time that such features have been seen. One possibility is that they are organic material that lubricates the connection between girdle bands. … This suggests to us that the beads are a lubricant because they only occur on the new bands. [21]

Biotribologists gather information about the tribology of biological systems and subsequently apply this knowledge to technological innovation as well as to the development of environmentally sound products [22]. Three key examples for biological model systems of possible interest to the tribologists are synovial joints (low friction coefficient), rolling switchable adhesion of white blood cells in the blood vessels and diatom (Figs. 2.1 and 2.7) tribology.

Regarding joint lubrication, friction coefficients as low as 0.001 have been reported [23–25]. However, especially in biological systems, friction and wear are not simply related phenomena [26, 27]: low friction systems do not necessarily result in low levels of wear. Low friction is in many cases more preferable than low wear since worn material can generally be replaced during the life-time of the single organism (but not in the diatoms).

The adhesion of leukocytes is mediated by switchable adhesion molecules and also by the force environment present in the blood vessel (leukocyte rolling, [28]). Initially, the leukocytes move freely along with the blood stream. Leukocyte adaptive adhesion involves a cascade of adhesive events commonly referred to as initial tethering, rolling adhesion (an adhesive modality that enables surveillance for signs of inflammation), firm adhesion, and escape from blood vessels into

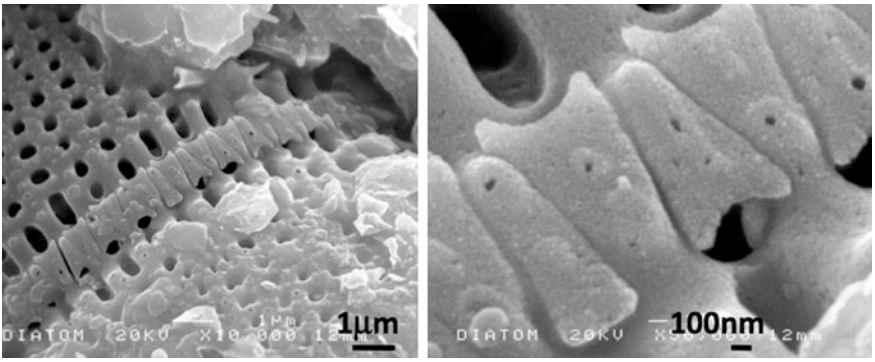

Fig. 2.7 *Left* Zipper-like biogenic silica structure in a diatom. *Right* Zoom into the same image. © Duncan Waddell, XTAL Enterprises, Australia. Image reproduced with permission

tissue [29]. Their rolling velocity is typically 10 to 100 times lower than a non-adherent leukocyte moving next to the vessel wall. The rolling is mediated by integrins, the most sophisticated adhesion molecules known.

In January 2005 the AIP Journal of Nanoscience and Nanotechnology published the special issue "Diatom Nanotechnology" [30]. There, *Ellerbeckia arenaria* who forms stringlike colonies that—when stretched and then released—swing back like springs, *Melosira* sp. who is an exquisite example for interlocking devices in single cells and between single cells, and *Bacillaria paxillifer*, a diatom that as colony actively moves through the water, were introduced as promising species regarding tribology on the micro- and nanoscale [31, 32].

Work on the interface between micro— and nanotribology and biology can be highly inspiring in completely unforeseen directions. The GEMS concept (GEMS stands for Group Electro-Mechanical Systems) for a MEMS-based virtual innervated system in materials was proposed in 2011 (Fig. 2.8), [33]. The fact that a huge body of tribologically relevant information is published in biology papers that are hard to access (in terms of language and concepts) for tribologists lead to the draft of a concept for new ways of scientific publishing and accessing human knowledge inspired by transdisciplinary approaches [34]. This new approach shall help to make biology more accessible for tribologists (and vice versa).

Biomimetics

The inventor of the Schmitt trigger, the American engineer, and biophysicist Otto H. Schmitt, coined the word 'biomimetics' in the 1980s [35]. Biomimetics denotes a method in science, engineering and the arts that gains inspiration from nature [36]. Nature is not blindly copied, but the basic principles are identified and transferred to the respective field. One very successful example for biomimetics and in fact the work that forms the basis of the current highly positive connotation

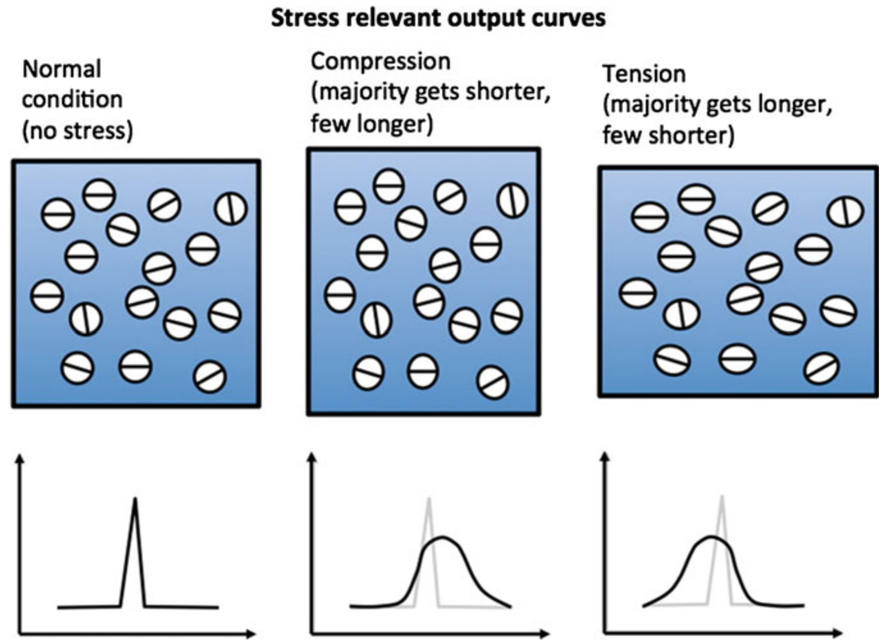

Fig. 2.8 Characteristic responses of a material innervated with Group Electro-Mechanical Systems (GEMS). Normal condition (*left*), compression condition (*middle*) and tension condition (*right*) can easily be discerned by measuring the external induction signal. The *top* images give a sketch of the GEMS embedded in the matrix, and the *bottom* images the characteristic resulting induction versus time curves [33]. © 2011 Trans Tech Publications Ltd. Switzerland. Own image reused with permission

of biomimetics in the general public is technological applications inspired by the self-cleaning property of the lotus leaf. Minuscule wax structures on the leaf surface yield a high contact angle for water droplets, which subsequently, if the surface is just slightly tilted, roll off, taking impurities with them [37]. Buddhists admire the purity of the lotus, and it is one of their sacred plants. Inspired by the surface structure of the lotus leaf, currently, various self-cleaning surface coatings and paints are on the market, and millions of liters of the facade paint Lotusan® by the STO company have been used in the recent years.

Biological materials are sophisticated, have a high degree of miniaturization and hierarchical organization, are resistant and adaptive. An example for a remarkably resistant and adaptive material is human skin—it protects the inside of our body, serves as "packaging", it is a barrier for hazardous molecules in the air but nevertheless allows water vapour to leave the body. It can self-repair and grow or shrink, be elongated by a certain amount and compressed. It controls the temperature of the body by adjusting the amount of vapour and/or sweat leaving the body, providing a cooling effect when needed. Generally, the hydrodynamic, aerodynamic, wetting and adhesive properties of biological materials are remarkable. Biomimetic principle-transfer to engineering paves the way for more reliable, efficient and environment-respecting materials [38]. The increased interest of engineers in the field is exemplified by various publications, e.g., the special issue on biomimetics in engineering in the prestigious British Proc. IMechE Part C Journal in 2007 [39].

Words that are increasingly important in engineering are “green” and “sustainability”. Also regarding tribology first attempts have been made to define the respective fields and to establish a framework of tasks that need to be accomplished so that the resulting tribology is “green” or “sustainable” [40–43]. Si-wei Zhang, past chairman of the Chinese Tribology Institution introduced the term “Green Tribology” in 2009 and Peter H. Jost stressed this field as of high importance for tribology at the 2009 Tribology World Congress in Kyoto, Japan.

Biomimetics is not inherently sustainable [44]. It is simply a method, and as such it is not connected with any value. Not surprisingly, some biomimetic materials are way less sustainable than their commonly produced counterparts—this comes from the fact that in living nature, sustainability emerges for the whole system, and not necessarily its single subsystems are sustainable. If we extract a principle from such a subsystem, and apply it to our technology, the result might even be dangerous. Therefore, especially in nanoscience, in nanotribology, in learning from nature on the nanolevel—which is the very level of nature’s language—accompanying technology assessment is of such high importance [45].

Biomimetic work has advantages for both biology and engineering, and there are various motivations for a dialogue [12]. It is necessary to establish a common language of biologists and engineers, in which descriptions at different level of detail are more compatible. The engineering approach with established knowledge about structure–function relationships and its application for technological optimization (lighter, faster, and cheaper) meets the biologists approach who gather basic knowledge to enhance the understanding of the principles of living systems: both have to do with constructions, processes and developments. Examples for successful biomimetic engineering come both from biomimetics by induction, i.e., solution based biomimetics, and biomimetics by analogy, i.e., problem based biomimetics, (Fig. 2.5) and technical biology. An intriguing example for biomimetics by analogy is winglets on airplanes. The engineering problem is the large turbulences induced by the wingtips of airplanes. The biological best practice example are big gliders such as storks. The solution in nature is that the feathers at the wingtips of these birds are arranged in a way that the lift-induced drag caused by wingtip vortices is minimized by dividing the large vortex into several smaller vortices. The principle transfer in engineering yields the winglets that are currently applied to many commercial airplanes. Further abstraction of the principle behind the winglets results in spiroids (split wing loops) [46] that considerably cut fuel consumption. A second example for biomimetics by analogy is the bioinspired straw bale screw [13]. Trees feature load-adaptive growth and maintain a uniform stress distribution at their surface. The surface stresses that arise from gravity and external sources are kept constant during their growth. When branches are cut or the environment changes (e.g., the tree tilts because the ground tilts) the tree continues to grow according to the principle of minimising surface stress peaks and this results in regaining uniform surface stresses. The biomimetically optimised screw for mounting façades and other items to straw-bale buildings was developed by applying a tree-inspired method to optimize work pieces [47]. Material use in this screw is minimised and toughness is increased in certain relevant cases of load by more than a third in comparison to a non-optimized geometry. An intriguing example for biomimetics by induction is Velcro. The Swiss engineer George de Mestral walked his dog in 1949, and was amazed by the fact how closely the fruits of a burdock stuck to the fur of his dog. Under the microscope he saw hundreds of tiny flexible but strong hooks that where thus able to reversibly attach themselves to textile and hairy structures. His bioinspired hook-and-loop fastening system was filed for patent in 1951 (Swiss patent # 295638) and de Mestral became a millionaire. A second example for biomimetics by induction is the self-cleaning surfaces and paints inspired by the lotus leaf (Barthlott and Neinhuis [37], US patent # 6660363). The example that [12] give concerning technical biology is the investigations on spiders that have been performed by Barth and co-workers for many decades (for review, see Barth [48, 49]. Biological sensors are amazing, concerning what they can sense and also concerning their bandwidth [50]. Single photon detectors [51] and mechanoreceptors with sub-nanometer sensitivity [52] are two examples. Biologists such as Barth use engineering methodology and approaches to elucidate the function of exquisite spider sensors such as the slit sensilla organs on the legs that act as biological strain gauges, the Trichobothria, hairs that measure medium flow with a threshold for the work driving a single receptor hair over one oscillation cycle of 2.5×10^{-20} J [48, 49] and spider tactile hairs, touch receptors that act as nonlinear sensors. This kind of approach is termed technical biology.

Karman et al. [53] propose a novel approach to MEMS that is based on biological sensory systems, to assist, enhance and expand human sensory perceptions. Current MEMS cover the range of the human sensory system, and additionally provide data about signals that are too weak for the human sensory system (in terms of signal strength) and signal types that are not covered by the human sensory system (Fig. 2.9).

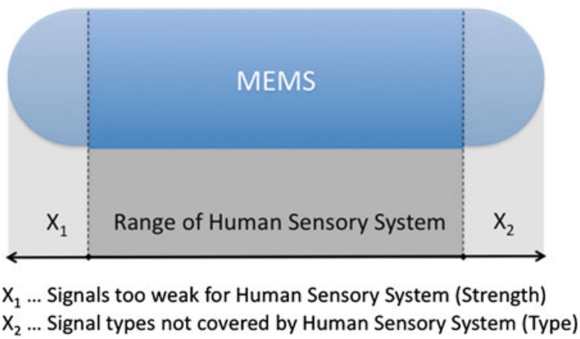

Fig. 2.9 Functional regions of smart MEMS sensors compared to the human sensory system [53]. © 2011 Trans Tech Publications Ltd. Switzerland. Own image reused with permission

Fig. 2.10 "The Soul of the Rose" by John William Waterhouse, public domain image. The sense of smell is one of the oldest senses in humans. Assistance, enhancement and expansion of this sense via MEMS open a whole new universe for engineering applications

Senses in organisms comprise vision (the human visible range is from 390 to 750 nm; various animals can see in the UV range, from 300 nm), temperature sensing (forest fire seeking beetles; snakes who "see" a temperature image with 250 × 250 pixels), hearing and echolocation (man: 20–20 kHz, mice up to 85.5 kHz, bats up to 120 kHz), smelling (Fig. 2.10; people have single molecule sensitivity; sharks can smell one drop of blood in the water 0.4 km away!), feeling touch and vibration, the magnetic sense (in more than 50 species such as migratory birds, honeybees, butterflies, snails, fish, sea turtles, cows, deer, salamanders, geckos, earthworms) and electroreception.

MEMS sensors on the market concerning these senses comprise MEMS that detect electromagnetic waves, temperature, sounds, smells, touch and vibration as well as flavours.

The technological and societal potential of biomimetics is treated in Stachelberger, Gruber and Gebeshuber [54]. The micro— and nanoscale is of utmost importance in relation to biological materials, structures and processes, and relating biomimetics. There is no guarantee that a technical solution based on biomimetics will be eco-friendly. However, biomimetics as an interdisciplinary scientific subject is thought to contribute to some extent to sustainable innovation [55]. Emergence as one of the key properties in biology can be put into relation with sustainable innovation, via a bridge of necessity to go well beyond the frontiers of classical disciplines, thought patterns and organizational structures. In order to introduce innovation principles into societal practice there is a need for ingenious and well-educated people as well as a proactive environment.

MEMS

Wear, friction and adhesion are major reliability issues in MEMS. Reasons are the high surface to volume ratio and the small mass of these devices. Human technology has just started to develop and utilize such small devices, and there are still various tribological issues that need to be addressed [56–60]. High performance microactuators, surface characterization, biosensors and microfluidic systems, MEMS materials and structures, the influence of water adsorption on the microtribology of micromachines, rheological modelling of thin film lubrication, nanotribology of vaporphase lubricants, the tribology of hydrocarbon surfaces investigated using molecular dynamics, surface force induced failures in microelectromechanical systems, reliability and fatigue testing of MEMS and general tribology issues and opportunities in MEMS are current hot topics of research. Especially concerning three-dimensional MEMS, we have not yet progressed very much since 1987, when Texas Instruments Digital Micromirror Devices were introduced to the market.

Various species of diatoms are excellent biological systems from which we can learn concerning tribology. Diatoms have rigid surfaces in relative motion, they are small and experience various forces from the environment [44, 61, 62]. For example, a most exquisite click-stop mechanism on the microscale in diatoms can be envisaged to have high inspirational potential regarding 3D MEMS, especially in constructing 3D MEMS from 2D structures, by folding and fixing them [4]. A zipper-like nanoclasp with high potential regarding 3D MEMS had recently been described by Tiffany and co-workers [63].

Learning from Nature for Tribology: A General Perspective

Although the worlds of tribologists and biologists increasingly get closer, some tribologists choose not to deal directly with animated nature. Even for such researchers, without having to deal with biology at all, some very general principles can be extracted and systematic technology transfer from biology to engineering thereby becomes generally accessible. The biologist Werner Nachtigall, the initiator of biomimetics in Germany, introduced ten general principles. These principles in biology comprise integration instead of additive construction, optimization of the whole instead of maximization of a single component feature, multi-functionality instead of mono-functionality, 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 [64].

Peter Fratzl and Julian Vincent identified the following recurring principles of biology: correlation of form and function, modularity and incremental change, genetic basis, competition and selection, hierarchy and multi-functionality [65, 66].

In 2002 our group investigated the adhesives some diatoms produce to attach to substrates [67]. We found that these adhesives are tough, strong and self-repairing, similar to the properties identified in the abalone glue by Smith and co-workers in 1999 (Fig. 2.11), [68]. The name 'Diatom Tribology' appeared first in one of our conference papers in 2004. In the initial works, species of high relevance to tribology were identified, including *Ellerbeckia arenaria* and *Bacillaria paxillifer* [31, 32]. In a Nano Today article on biotribology inspiring new technologies, diatoms, the switchable cell adhesion molecules selectin and integrin, white blood cells rolling on the endothelium (rolling adhesion) and the dry adhesives of the gecko foot and certain insect attachment pad were introduced as best practice examples from nature [69]. The list of best practice organisms regarding tribology was widened in 2008 [22] by the amazing tribological properties of cartilage (where the friction coefficient can be as low as 0.001, see, e.g., [23–25], the crack redirection properties of the horse hoof that is based on the hoof nanostructure

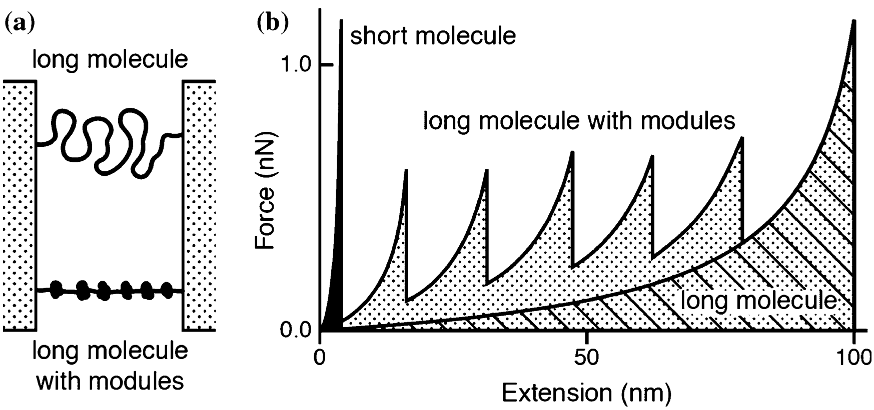

Fig. 2.11 Concept for a self-repairing adhesive [68]. **a** Two ways to attach two particles: with a long molecule or with a long molecule with nodules. **b** When stretched, a *short* molecule could just be extended a bit, and would then break. A *long* molecule would be stretched much more, and finally break. However, a *long* molecule with nodules, with sacrificial bonds that break before the backbone of the molecule breaks, increases the toughness of the adhesive. Such a strategy is applied in the abalone shell, and also in diatom adhesives. Reprinted by permission from Macmillan Publishers Ltd: Nature [68], copyright 1999

(tailored shape of wear particles; [70, 71]) and single huge biomolecules with molecular precision [72].

Gebeshuber, Majlis and Stachelberger investigated in 2009 tribology in biology regarding biomimetic studies across dimensions and across fields [61]. Biotribology is important in addressing tribological challenges at all length scales. The authors apply the Biomimicry Innovation Method to selected current tribological challenges and give ten functions, related biologized questions and nature's best practices concerning optimally designed rigid micromechanical parts (for 3D-MEMS). Regarding pumps for small amounts of liquid (for lab-on-a-chip applications) *Rutilaria philipinnarum*, a fossil colonial diatom that is thought to have lived in inshore marine waters, is identified as best practice organism (for details, see Srajer, Majlis and Gebeshuber [73]).

This type of approach is intensified in a 2011 book chapter [10]. "Biomimetics in Tribology" starts with the historical background (Fig. 2.12) and current developments. The authors present the huge unexplored body of knowledge concerning biological publications dealing with 'wear' and 'adhesives' that make in the text no obvious connection to tribology (Fig. 2.13).

More than 100 references point to a multitude of best practices from nature concerning meliorated technological approaches of various tribological issues. As next step, detailed investigations on the relevant properties of the best practices and extraction of the underlying principles are proposed. Such principles shall then be incorporated into devices, systems and processes and thereby yield biomimetic technology with increased tribological performance.

Fig. 2.12 1771 crash of Nicolas Joseph Cugnot's steam-powered car into a stonewall. Cugnot was the inventor of the very first self-propelled road vehicle, and in fact he was also the first person to get into a motor vehicle accident. Public domain image

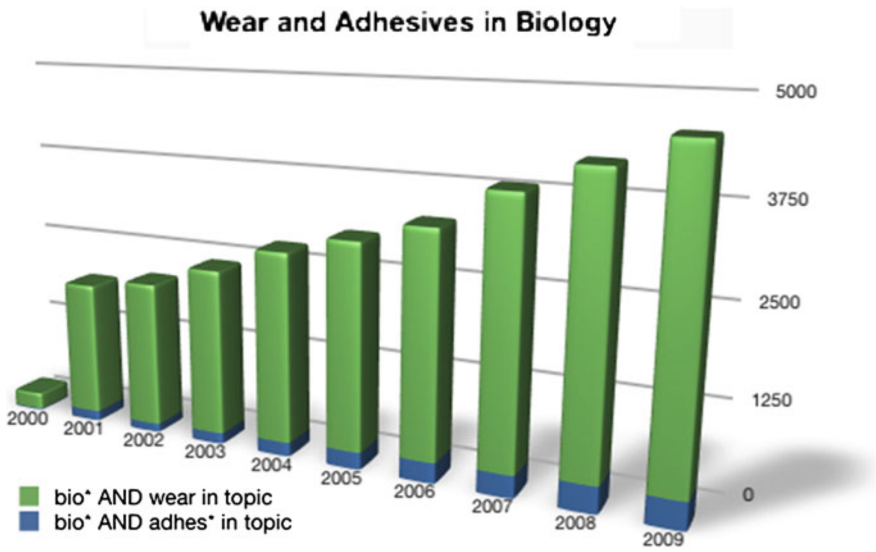

Fig. 2.13 The number of scientific publications in the years 2000–2008 dealing with either wear or adhesives in biology comprise a huge yet unexplored amount of inspiration for technology. *Source* ISI Web of Knowledge, Thomson Reuters, Citation Databases: SCI-EXPANDED (2001-present), CPCI-S (2004-present). http://www.isiknowledge.com (accessed May 5, 2010; Gebeshuber and Majlis [34]). © 2010 W. S. Maney and Son Ltd. Own image reused with permission

Learning from Nature Regarding MEMS Tribology: A Specific Perspective

More often than not, tribological issues prevent successful commercialization of 3D MEMS systems and are the reason why most 3D MEMS are still in prototype stage.

Already in the year 2000 Scherge and Gorb evaluated the adhesion between an insect foot and a variety of surfaces and suggested, inspired by flexible biological micromechanical units found in the attachment pads of the bush cricket, using biological principles to design MEMS [74]. Subsequently they published their book on biological micro— and nanotribology [11]. In 2007, Nano Today invited the author of this chapter to review work on inspiring organisms regarding bio-tribology. Biotribolological examples with functional units on the micro— and nanometer length range and bioinspired technological development are presented [69].

Engineers and materials scientists can learn by watching, imitating, understanding and generalizing natural approaches to challenges and propose new technology that is recyclable and sustainable, reliable and energy efficient.

As mentioned above, regarding MEMS development, diatoms, the creators of glass castles, can serve as biotribological model systems. Diatoms are unicellular microalgae with a cell wall consisting of a siliceous skeleton enveloped by a thin organic case [3]. Each single diatom cell “lives in a silica box” with an upper and a lower part. When the cell is dividing, a new lower part for the previous upper part and a new upper part for the previous lower part is biomineralized, with the old parts being a bit larger than the newer ones. There are tens of thousands of different diatom species, with a huge variety in shapes and sizes (from some micrometers up to several millimeters). What makes diatoms interesting concerning 3D MEMS development is the fact that they produce the siliceous skeleton just once, and do not repair it. The silica box is hard, tough and rigid, and a multitude of nanostructures, hinges and interlocking devices occur in various species. Some colonial diatom species even act like rubber bands when elongated and subsequently released [32]. Other diatom species exhibit strong, self-repairing underwater adhesives [67]. Some diatom species such as *Pseudonitzschia* sp. and *Bacillaria paxillifer* (the former name of this diatom is *Bacillaria paradoxa,* because if its unusual behavior) are even capable of active movement, with no signs of wear ever detected.

A major issue in MEMS development is adhesion. Understanding this phenomenon on the molecular level not only contributes to improved micro— and nanodevices that do not aggregate or get stuck, but also might aid in the development of tailored man-made adhesives for example in tissue engineering where good adhesive interaction of the implant surface with the surrounding tissue is a necessity and implants should not cause immune reactions via small wear particles [75]. In this regard we can learn from the adaptive adhesion properties of the selectin/integrin complexes exhibited in the interaction of white blood cells with blood vessels.

Biologically inspired technical systems comprise a selectin/integrin inspired technique for cell separation used in lab-on-a-chip applications [76]. This technique involves a microfluidic channel where the silicon surface was functionalized with physisorbed selectin molecules, and thereby captured cells that exhibited integrin molecules. The microfluidic device consisted of arrays of micropillars (made from silicon prepared via deep reactive ion etching) with characteristic spacing somewhat larger than the size of cells (some tens of micrometers in diameter). Control experiments showed no non-specific adhesive interactions between the cells and the microchannels.

Work on the gecko foot by Autumn and colleagues [77, 78] inspired dry adhesives that work via intermolecular van der Waals forces and therefore act between all materials. However, man-made gecko tapes still cannot compete with the adhesive properties of the gecko foot concerning high attachment forces and low detachment forces, rough surface adaptation, self-cleaning ability and durability [79]. The group of Andre K. Geim, the 2010 Physics Nobel Prize winner concerning graphene, is working on improved gecko tapes [80].

In 2009 a novel way to describe the complexity of biological and engineering approaches depending on the number of different base materials was proposed [34, 61, 62]. Approaches in nature and technology can be categorized into material dominated, form dominated and structure dominated ones. When many different

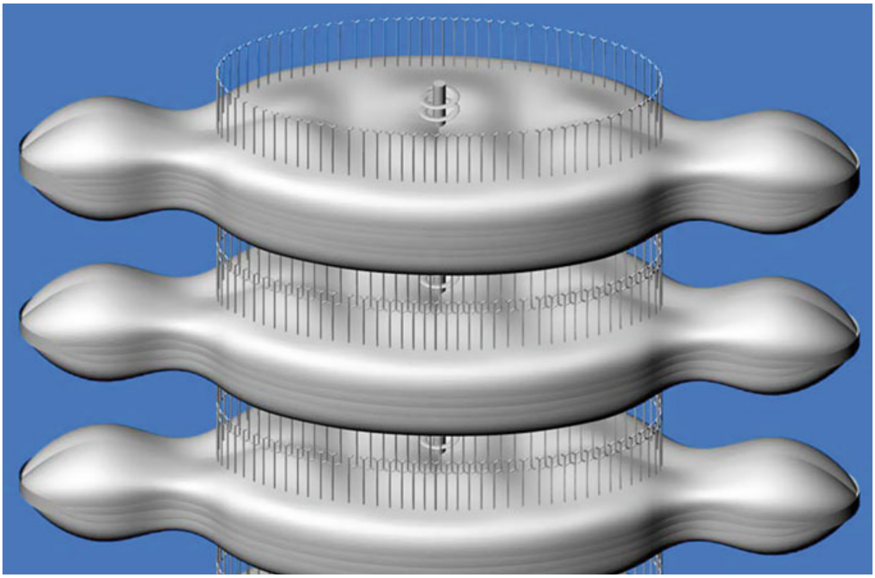

Fig. 2.14 Fluid dynamic simulation of colonial micrometer sized *boxes* (inspired by diatoms that are connected via spacers that ensure minimum and maximum distance) start to exhibit pumping behaviour when water flows along the chain [73]. © 2009 Acta Botanica Croatica. Own image reproduced with permission

materials are or can be used, there is no need to work too much with structures—most of the functions can be accommodated with the materials themselves. This is the approach in most of current technologies on the meso— and macroscale. On the microscale, e.g., for MEMS development, we have to work with just a handful of materials that we can structure, tailor, etch as we want them (e.g., Si, SiO_2, Silicon nitride, GaAs, Silicon carbide, diamond, InP, SiGe, ferroelectric materials and polymers). In MEMS, structures are dominating and accommodate most of the functions. In this regards, MEMS and organisms are highly similar. Also in living nature, just a few base materials are used, and either slightly chemically varied to accommodate specific functions (such as the material in the cornea, in our hairs and in our fingernails, keratin) or the base materials are (nano) structured or hierarchically structured, to accommodate desired functions. Therefore it is concluded that biomimetics is especially promising in MEMS development because of the material constraints in biology and micromachining.

Srajer and coworkers showed in 2009 via microfluidic simulation of a colonial diatom chain that oscillatory movement occurs when water flows along the chain (Fig. 2.14), [73]. The model diatom colony consists of continuously repeated units of ten cells. Undisturbed fluid flow is allowed for between the single cells, and the cells do not actively move—they are solely moved by the water. The computer simulation suggests that a diatom colony subjected to water flow exhibits some kind of oscillatory movement. Such movement might facilitate nutrient uptake of the diatom colony. If in this modelling study one replaces the word “diatom” with “MEMS black box”, the result is a microfluidic pump that might be of benefit for lab-on-a-chip applications and potentially also in addressing the problem of how to get rid of excess heat in MEMS (convection problem).

Bioinspiration for tribological systems on the micro- and nanoscale can be addressed by a highly structured approach, categorizing the functions into dynamic, mechanical, surface and structure related ones [81]. Bioinspiration for MEMS tribology is thereby assisted by a new way to analyse best practice biological materials, structures and processes that were established via the biomimicry innovation method, by relating them to four main areas relevant for MEMS and related microsystems development. When applying the biomimicry innovation method regarding a certain device to be optimized, a complete list of related functions is the basis for comprehensive quality improvement for the technology of choice. Table 2.1 presents four representative examples for the four main areas (a comprehensive treatment of MEMS issues via the biomimicry innovation method has yet to be performed). Behind each of the organisms given in Table 2.1 is a huge body of scientific literature and various experts, many of whom have devoted their whole scientific life to studying one single genus or species. Detailed literature searches for archival scientific work and specialists in these fields provide the starting points for collaborative approaches.

It is suggested that the tribology engineers get in contact with the respective biologists working on the organism of interest, perhaps with the additional support of a person who is experienced in biomimetics and in speaking with representatives of both fields. Strong collaboration between biologists and engineers can yield new, sustainable approaches to emerging micro- and nanotechnologies and provide the basis for a new type of scientist/researcher/developer, who understands and feels at home in various fields, and who can transfer concepts and principles across fields. Such people are highly needed in our current time of increasing specialisation.

Summary and Outlook

Biology for tribologists interested in MEMS tribology and materials issues has to be written and categorized in a different way than biology for biologists. Functions are important, as are the relations of structures with functions. Some authors such as Tributsch, Vogel, Alexander and Nachtigall managed to publish works on biology that are highly accessible to engineers [64, 82–89]. These works can serve as a starting point for tribologists who want to learn from nature for improving MEMS tribology and materials issues.

There is a great future ahead of us concerning MEMS. Learning from nature might even yield in the not too distant future sustainable MEMS with expiration date, MEMS that only work as long as we need them, MEMS that are built from substances that are generally available and cheap as well as MEMS that are structured via bottom up technologies based on self-assembly.

Table 2.1 Examples for bioinspiration in MEMS tribology and related fields (from Gebeshuber and Gordon [81])

Area	Function	Biologized question: How does nature...	Nature's best practice	Generated process/product ideas
Dynamic	Movable rigid parts	optimize moveable parts?	The diatoms *Melosira* sp. and *Ellerbeckia arenaria*	3D MEMS with moveable parts
	Pumps	move small amounts of fluids?	The diatoms *Rutilaria grevilleana* and *Rutilaria philipinnarum*	Micropumps for lab-on-a-chip applications
	Energy dissipation in microsystems	dissipate mechanical energy in microorganisms?	The diatom *Solium exsculptum*	3D-MEMS
	Lubrication	prevent wear?	Unknown diatom species	Preventing stiction
Mechanic	Hinges and interlocking devices	mechanically connect hard single cells on the microscale?	Diatoms in chains (*Eunotia sudetica, Bacillaria paxillifer, Ellerbeckia sp.*)	Micromechanical optimization of 3D-MEMS structure
	Click-stop mechanism	unfold microstructures and then irreversibly fix them?	The diatom *Corethron pennatum*	Obtain 3D structures from fabricated 2D structures
	Springs	reversibly store mechanical energy?	*Rutilaria grevilleana* and *R. philipinnarum*; the spasmoneme of *Vorticella convallaria*	Energy storage in MEMS
	Parts connected in a chain with adjustable length	provide stability to chains in turbulent environments?	The diatom *Ellerbeckia arenaria*	MEMS with moveable parts
Surface	Surface texturing	structure surfaces?	The diatom *Solium exsculptum*	MEMS
	Photoprotective coating	protect photo-sensitive plants?	The flowering plants *Begonia sp., Diplazium sp., Phyllagathis rotundifolia*	Coatings of containers for photosensitive reactions
	Photonic components	make structural colours?	Peacock, butterfly scales, iridescent plants, fruits, birds and mammals	Photonic micro- and nanodevices, MEMS, novel lasers
	Selective, switchable adhesion	reversibly adhere to structures?	Immune system, gecko foot, insect attachment pads, plant wax surfaces	Lab-on-a-chip devices, reusable: trap, test and release and start again

(continued)

Table 2.1 (continued)

Area	Function	Biologized question: How does nature...	Nature's best practice	Generated process/product ideas
Structure	Unfoldable microstructures	generate 3D microstructures from rigid parts?	The diatom *Corethron pennatum*	Obtain 3D structures from fabricated 2D structures
	Stability (reinforcement)	mechanically protect viable parts?	The diatom *Solium exsculptum*	Quality assurance of MEMS
	Mechanical fixation	mechanically fix structures on the microscale?	The diatom *Corethron pennatum*	3D-MEMS, lab-on-a-chip
	Pressure resistant containers	deal with high pressures?	*Euglena gracilis* pellicle	Lab-on-a-chip

H. Peter Jost, president of the International Tribology Council, addressed at the 5th World Tribology Congress in Kyoto in September 2009 the situation surrounding the world and green tribology, declaring:

> 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. [90]

Jost explained in Kyoto that there were now production requirements concerning the supply of energy, mineral resources and food in a way which had not been known before. A focus on tribology might give 'breathing space' while comprehensive solutions to environmental problems were being addressed and suggested that tribology must fall into line with the major politics of world environment and energy.

A smart combination of mechanical, energetic and chemical approaches, combined with optimum designed materials, and minimized stresses to the environment and biology, paves the way towards the future of MEMS tribology and material issues. Successful tribologists are inherently transdisciplinary thinkers—this is needed in our increasingly complex world to successfully contribute to address major global challenges.

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