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Chapter 3
Biomimetics in Tribology

I.C. Gebeshuber, H.A. Abdel-Aal, B.Y. Majlis, and H. Stachelberger

Abstract Science currently goes through a major change. Biology is evolving as new Leitwissenschaft, with more and more causation and natural laws being uncovered. The term 'technoscience' denotes the field where science and technology are inseparably interconnected, the trend goes from papers to patents, and the scientific 'search for truth' is increasingly replaced by search for applications with a potential economic value. Biomimetics, i.e. knowledge transfer from biology to technology, is a field that has the potential to drive major technical advances. The biomimetic approach might change the research landscape and the engineering culture dramatically, by the blending of disciplines. It might substantially support successful mastering of current tribological challenges: friction, adhesion, lubrication and wear in devices and systems from the meter to the nanometer scale. A highly successful method in biomimectics, the biomimicry innovation method, is applied in this chapter to identify nature's best practices regarding two key issues in tribology: maintenance of the physical integrity of a system, and permanent as well as temporary attachment. The best practices identified comprise highly diverse organisms and processes and are presented in a number of tables with detailed references.

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As next step, detailed investigations on the relevant properties of the best practices identified in this chapter shall be performed, and the underlying principles shall be extracted. Such principles shall then be incorporated into devices, systems and processes; and thereby yield biomimetic technology with increased tribological performance. To accelerate scientific and technological breakthroughs, we should aim at having a context of knowledge: the gap between scientific insights and technological realization should be bridged. To prevent being trapped in the inventor, innovator or investor gaps, a cross dialogue is necessary, a pipeline from 'know-why' to 'know-how' to 'know-what'. This is specifically of relevance in tribology, since tribological research is ultimately linked to real-world applications. Applying biomimetics to tribology could provide such a pipeline.

3.1 Introduction: Historical Background and Current Developments

Science currently goes through a major change: in biology, more and more causation and natural laws are being uncovered [1]. Biology has changed during the recent decades: it transformed from a rather descriptive field of research to a science that can – in terms of concepts, basic ideas and approaches – be acknowledged and understood by researchers coming from 'hard sciences' (such as physics, chemistry, engineering and materials science) including tribologists (Fig. 3.1) [2]. Tribology relies on experimental, empirical, quantifiable data or the scientific method, and focuses on accuracy and objectivity [3, 4]. The amount of causal laws in this new

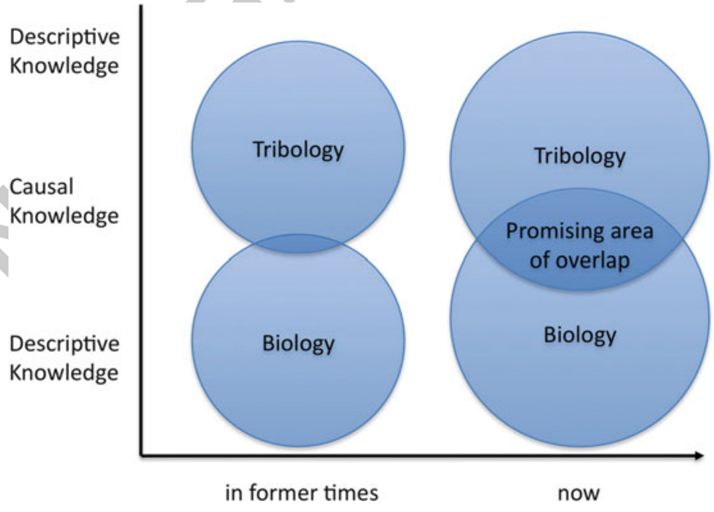

Fig. 3.1 The increasing amount of causal laws in biology generates promising areas of overlap with tribology

biology (indicated by the ratio of causal vs. descriptive knowledge) is steadily growing and a new field that can be called ‘Biological Physics’ is emerging [1]. The languages of the various fields of science increasingly get compatible, and the amount of collaborations and joint research projects between researchers coming from the ‘hard sciences’ and biologists have increased tremendously over the last years. Still, there is a large gap between the natural sciences and humanities [5].

The term ‘technoscience’ characterizes a field in which technology and science are inseparably interconnected. This characteristic hybrid form is, for instance, seen in the atomic force microscope – a symbol for both nanoscience and nanotechnology. This tool not only allows for basic scientific investigations, but also for manipulation and engineering at very small scales. In technoscience, there is no clear distinction between investigation and intervention. Even more, by investigation already interventions may be made. Application-oriented biomimetics can be denoted as ‘technoscience’.

Traditionally, engineers are interested in what works, i.e. what functions and is useful, and are hence rather pragmatic, whereas scientists are interested in explanations, hypotheses and theories that reflect a rather different stance. For scientists, experiments are meant to try and prove or falsify a hypothesis or theory. The practical aspects of experiments, i.e. the potential applicability, do not belong to science but to technology. ‘While traditional conceptions of science foreground the formulation and testing of theories and hypotheses, technoscience is characterized by a qualitative approach that aims to acquire new competencies of action and intervention’ [6]. Of course, also pure scientific theories are a basis or prerequisite for technology, but it is not necessary to have an application in mind before a scientific investigation, which is a characteristic of the field of technical biology [7]. Living nature is seen from an engineering viewpoint, or even nature itself is thought of as an ‘engineer’ who is facing technical problems.

In biomimetics, materials, processes and systems in nature are analyzed; the underlying principles are extracted and subsequently applied to science and technology [7–10]. Biomimetics is a growing field that has the potential to drive major technical advances [1, 11, 12]. It might substantially support successful mastering of current tribological challenges. The biomimetic approach can result in innovative new technological constructions, processes and developments [7]. Biomimetics can aid tribologists to manage the specific requirements in systems or product design, to integrate new functions, to reduce production costs, to save energy, to cut material costs, to redefine and eliminate ‘waste’, to heighten existing product categories, to define new product categories and industries, to drive revenue and to build unique brands [13, 14].

Gebeshuber and Drack [7] distinguished two methods of biomimetics: biomimetics by analogy and biomimetics by induction, to which the different activities in the field can be assigned. Biomimetics by analogy starts with a problem from technology and tries to find analogous problems in nature with the respective solutions that might also be useful in the technology. Biomimetics by induction refers to ideas that stem from basic science approaches in biology, with no intention for applications as a motivation in the first place.

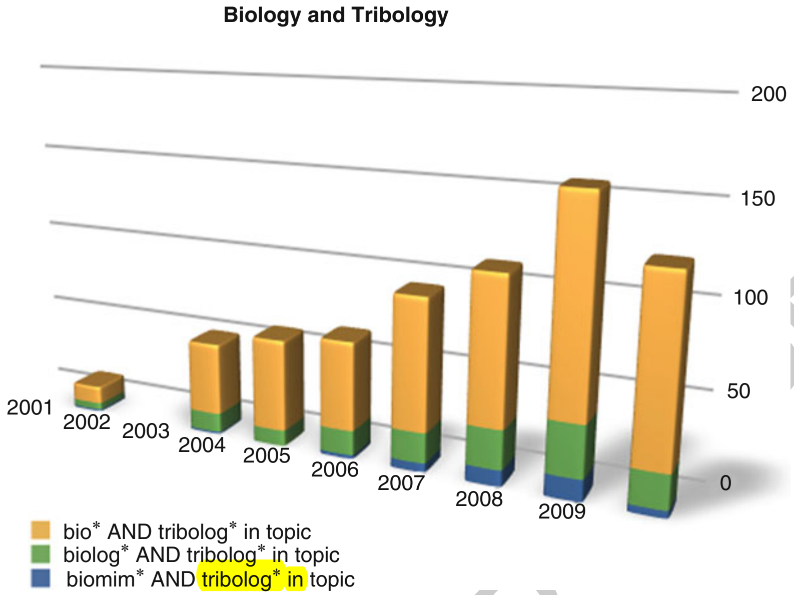

Fig. 3.2 The number of scientific publications in the years 2001–2008 with explicit relation between biology and tribology
Source: ISI Web of Knowledge, Thomson Reuters, Citation Databases: SCI-EXPANDED (2001-present), CPCI-S (2004-present). http://www.isiknowledge.com, (accessed 5 May 2010)

Biomimetics is yet another example for the increasing dissolution of disciplines that are found in science, together with the development of highly specialized domains. Interdisciplinary work with a specific focus (e.g. the functional design of interacting surfaces by means of nanotechnology) requires input from more than one classical discipline (in this example: physics, chemistry, biology, mechanical engineering, electronics and tribology). Recurrent concepts in biomimetics can easily be transferred to technology [1, 7, 8].

The amount of scientific papers that link biology to tribology is increasing (see Fig. 3.2). However, there is still a large unexplored body of knowledge that deals with lubrication and wear in biology but that has not yet been linked extensively to technology (Fig. 3.3).

3.2 Biology for Engineers

Engineers may not be primarily interested in evolution or taxonomy. Yet, basic knowledge about typical reactions of biological organisms or groups of organisms to conditions imposed by natural and human activities might prove beneficial for their work. Biology for engineers should be principle-based, viewed as a system

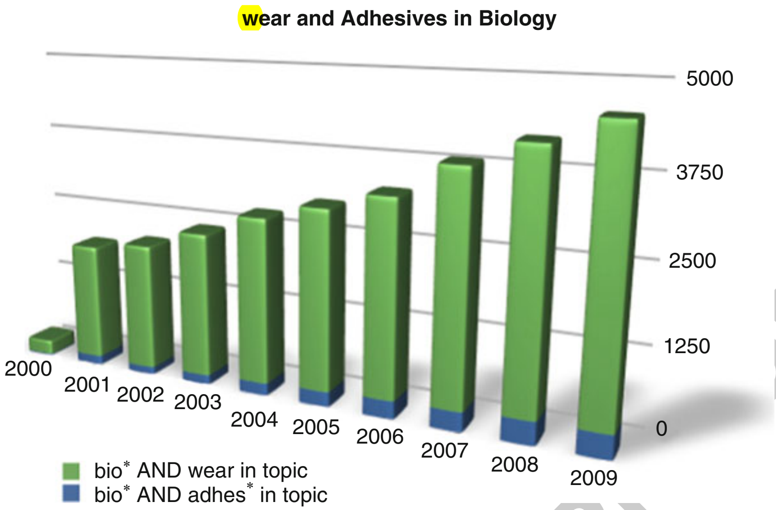

Fig. 3.3 The number of scientific publications in the years 2000–2008 dealing with either wear or adhesives in biology comprise a huge yet unexplored amount of inspiration for technology *Source*: ISI Web of Knowledge, Thomson Reuters, Citation Databases: SCI-EXPANDED (2001-present), CPCI-S (2004-present). http://www.isiknowledge.com, (accessed 5 May 2010)

and might lead to predictive expectations about typical behavioural responses [15, Table 3.1].

Recurring principles of biology are correlation of form and function, modularity and incremental change, genetic basis, competition and selection, hierarchy and multi-functionality [16, 17].

General principles that can be applied by engineers who are not at all involved in biology have been distilled [18]. These basic principles comprise integration instead of additive construction, optimization of the whole instead of maximization of a single component feature, multi-functionality instead of mono-functionality, energy efficiency and development via trial-and-error processes. Systematic technology transfer from biology to engineering thereby becomes generally accessible.

Knowledge about the responses of biological systems may lead to useful products and processes, might increase the ability of engineers to transform information from familiar systems to unfamiliar ones and might help to avoid unintended consequences of emerging technologies.

Nachtigall promoted analogy search and states that the nature of qualitative analogy research is an impartial, open-minded comparison. He presents numerous examples of insect micromorphology and relates functional mechanisms to technological examples in a visual comparison [19].

In biomimicry, nature is seen as model and mentor (and measure for sustainability). Models in nature are studied, and forms, processes, systems and strategies are emulated to solve human problems – sustainably. Biomimicry is a new way of viewing and valuing nature. It introduces an era based not only on what we can

Table 3.1 Possible extrapolation of biological responses to technical systems

Biological responses [15]	Possible extrapolation to technical systems
Organisms die without water, nutrients, heat sources and sinks and the right amount of oxygen	Proper energy management
Organisms become ill in the presence of wastes	Proper waste management
Organisms modify their environments	Consider two way interaction of device with environment
Extra energy will be spent on adaptations	Rather adapt than completely change
Organisms, if possible, will move to friendlier environments	Choose promising niches
Organisms will evolve under environmental pressures	Reactive responsive adaptive devices
Crowding of organisms produces stress	Information management in an era of over-information
Organisms are affected by chemical and mechanical stresses	Reactive devices
Optimization is used to save energy and nutrient	Resourcefulness
Organisms alter themselves to protect against harsh environments	Adaptive devices
Organisms cooperate with other organisms	Sharing of data and results with other devices in the same system
Organisms compete with other organisms	Input from other devices is used to improve respective device
Organisms reproduce	Develop self-replicating devices
Organisms coordinate activity through communication	Communication of devices with each other to eliminate abundances
Organisms maintain stability with exquisite control	Feedback mechanisms inside the devices and within the system
Organisms go through natural cycles	Emerging technologies go through circles from primitive to complex to simple
Organisms need emotional satisfaction and intellectual stimulation	Technology should be helpful, and not a burden (cf. openability issues)
Organisms die	Develop materials with expiration date

extract from the natural world, but also on what we can learn from it [20], for example related to developing better brakes. Not only in 1771 this was an issue (see Fig. 3.4), optimizing brakes is still important today.

3.3 Method: The Biomimicry Innovation Method

The biomimicry innovation method (BIM, [21]) is a successful method in biomimetics. This method is applied here to identify biological systems, processes and materials that can inspire tribology. Biomimicry is an innovation method that

Fig. 3.4 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

seeks sustainable solutions by emulating nature's time-tested patterns and strategies. The goal is to create products, processes and policies – new ways of living – that are well adapted to life on earth over the long haul.

The steps in BIM are as follows: Identify function, biologize the question, find nature's best practices and generate product ideas.

Identify Function: The biologists distil challenges posed by engineers/natural scientists/architects and/or designers to their functional essence.

Biologize the Question: In the next step, these functions are translated into biological questions such as 'How does nature manage lubrication?' or 'How does nature bond parts together?' The basic question is 'What would nature do here?'

Find Nature's Best practices: Scientific databases as well as living nature itself are used to obtain a compendium of how plants, animals and ecosystems solve the specific challenge.

Generate Process/Product Ideas: From these best practices, the biologists generate ideas for cost-effective, innovative, life-friendly and sustainable products and processes.

The BIM proves highly useful in habitats with high species variety and therefore high innovation potential (e.g. in the tropical rainforests or in corral reefs), providing a multitude of natural models to learn from and emulate. According to the experience of the US based Biomimicry Guild, about 90% of the generated process/product ideas are usually new to their clients (who include companies such as Boeing, Colgate–Palmolive, General Electric, Levi's, NASA, Nike and Procter and Gamble).

There is an abundance of biological literature available. However, only a few of these works concentrate on the functions of biological materials, processes, organisms and systems [19, 22–27]. The Biomimicry Guild is currently undergoing a major endeavour and collects on its web-page http://www.asknature.org 'strategies of nature' together with scientific references and envisaged and already existing bioinspired applications in industry. The 1,245 strategies (status 5 May 2009) are grouped in 8 major sections and comprise answers to the questions

How does nature break down?
How does nature get, store or distribute resources?
How does nature maintain community?
How does nature maintain physical integrity?
How does nature make?
How does nature modify?
How does nature move or stay put?
How does nature process information?

Strategies in ‘How does nature maintain community?’ of relevance regarding tribology are concerned with maintenance of physical integrity, management of structural forces and prevention of structural failure (Table 3.2). Strategies in ‘How does nature move or stay put?’ with most relevance regarding tribology are concerned with attachment (Table 3.2). The results section below presents the outcome of a thorough screening of these strategies and subsequent clustering and further analysis of especially promising ones regarding tribology.

3.4 Results: Biomimetics in Tribology – Best Practices and Possible Applications

Application of the BIM concerning wear, shear, tension, buckling, fatigue, fracture (rupture), deformation and permanent or temporal adhesion yields a variety of best practices that comprise biological materials and processes in organisms as diverse as kelp, banana leafs, rattan, diatoms and giraffes (Tables 3.3–3.9).

Table 3.2 Structure of the strategies on AskNature.org relevant for tribology used in this work

Major category	Category	Sub category
Maintain physical integrity (799)	Manage structural forces (289)	Mechanical wear (30)
		Shear (16)
		Tension (28)
	Prevent structural failures (52)	Buckling (14)
		Deformation (4)
		Fatigue (4)
		Fracture (rupture) (30)
Move or stay put (43)	Attach (102)	Permanently (41)
		Temporarily (61)

The numbers indicate the total amount of strategies in the respective categories (status 5 May 2010).

Table 3.3 Application of the biomimicry innovation method regarding mechanical wear

Biologized question: How does nature …	Nature's best practice	Generated process/product ideas	
… build flexible anchors?	Anchor has flexibility: bull kelp [34]	Bioinspired wave and tidal power systems [35]	t3.1
… lubricate fast moving parts?	Chameleon tongues move with an acceleration of 50 g and are lubricated [36, p. 70]	Lubrication in bionanotechnological devices, fast actuators	t3.2
… protect seeds from wear?	Seed coat: lotus (*Nelumbo nucifera*) [37]	Packaging	t3.3
… protects trees from damage?	Resin protects damage: conifer trees [38]	Packaging	t3.4
… lubricate joints?	Coefficient of friction in hip joints: 0.001 [39–41]	Technical joints, hip implants	t3.5
… prevent wear in abrasive conditions?	Skin exhibits low friction: sandfish skink [42]; optimized tribosystem: snake skin [43–45]	Abrasive cutting cools, adaptation in plateau honed surfaces [46]	t3.6
… maintain sharpness of teeth?	Teeth are self-sharpening: American beaver [47], sea urchins [48]	Self-sharpening tools, abrasive cutting cools, self-sharpening hand and power saws [49]	t3.7
… maintain low friction in nanoscale parts in relative motion?	Moving parts are lubricated: diatoms [50]	3D-MEMS [51]	t3.8
… protect soft matter against wear?	The skin of cartilaginous fish (*Elasmobranchii*) is protected by a covering of abrasive placoid scales, called denticles [52, p. 91]; Skin and mucus prevent abrasion: blennies [53].	Self-sharpening tools, abrasive cutting cools, industrial-grade sanders	t3.9
… protect bodies from dirt particles?	The body and eyes of stonefly larvae (*Capniidae*) are protected from sediment particles by a coating of dense hairs and bristles [54, p. 115].	Surface layer of devices that come in contact with abrasive particles	t3.10
… control wear of teeth?	Long-lived grazers with a side-by-side layered arrangement of enamel, dentine and cement [25, p. 333]	Agricultural tools	t3.11
… protect skin when burrowing?	Webbed feet of the platypus (*Ornithorhynchus anatinus*) are used for burrowing by folding back the webbing to expose the claws for work [55]	Protect equipment from damage, or from damaging something it comes into contact with when not in use. Gloves	t3.12
… protect folded structures from wear?	Insect wings [56]	Packaging, manufacturing, transport	t3.13
… protect soft structures from thorns?	Leathery tongue (*Giraffa camelopardalis*) [57, p. 61]	Soft but durable packaging replacing hard plastics	t3.14

Possible application scenarios are presented in the third column of this table.

Table 3.4 Application of the biomimicry innovation method regarding shear

Biologized question: How does nature . . .	Nature's best practice	Generated process/ product ideas
. . . reinforce materials?	Spiral fibres strengthen tree trunks [59, pp.28–29]: pine; circular, tapering beams stabilize: plants [60]; Nature achieves high flexural and torsional stiffness in support structures, with minimum material use, by using hollow cylinders as struts and beams [25, p. 440].	Tough materials
. . . prevent structures from breaking?	Stretchable architecture resists breakage: bull kelp [61]; joint shaped as suction cup prevents peeling: bull kelp [25, p. 425], Variable postures aid intertidal zone survival: sea palm [25, p. 435]	Tough materials
. . . build lightweight?	Lightweighting: Scots pine [62]; Bones are lightweight yet strong: birds [63]	Lightweight structures and materials
. . . resist shear?	Insect elytra resist shear and cracking: beetles [64]; tissues resist bending under stress: giant green anemone [65]; pulled support stalks have low flow stress: algae [25, p. 437; 66]; Leaves resist bending: trees, p. 580]; Many organisms, including limpets, resist shearing loads temporarily in part thanks to Stefan adhesion, which occurs when a thin layer of viscous liquid separates two surfaces [25, p. 427].	Shear resistant materials

Multifunctionality is a key property in biological entities. Therefore, many organisms and strategies are relevant for more than one tribological issue and therefore also appear in more than just one of the tables given below.

The inspiring organisms, ecosystems and natural structures and functions lay a sound foundation to proceed to the next step: detailed experimental investigation of the phenomena of interest. Further analysis concerning the rich flora in Southeast Asia by one of the authors (ICG) might provide further useful input concerning novel approaches regarding tribology. Valuable literature in this regard is available in abundance [e.g. 28–30] and personal presence in Malaysia with direct contact to devoted naturalists such as H.S. Barlow with his 96 acres Genting Tea Estate where he plants rare species and provides perfect environment for his objects of study prove highly beneficial for biomimetics work.

Increasing awareness about the innovation potential of the rainforest might also hopefully cause a paradigm shift in the way locals view the pristine forests. With the fast pace people are currently cutting down pristine tropical forests (e.g. in Asia or Brazil) and the subsequent extinction of a multitude of species, many of which are even not yet known to the public, many inspiring plants and animals

Table 3.5 Application of the biomimicry innovation method regarding tension

Nature's best practice	Generated process/ product ideas
Stretchable architecture resists breakage: bull kelp [61]; Stretching mechanism prevents fracture: blue mussel [67]; Two-phase composite tissues handle tension: pipevine [68]; Membranes get fatter when stretched: cells [69]; Arterial walls resist stretch disproportionately: cephalopods [25, pp. 7–8];	Stretchable materials
After too much tension is applied: Bones self-heal: vertebrates [70]; Diatom adhesives self-heal [71]	Self-healing materials; Self-healing coatings [72]
Walls prevent collapse under tension: plants [73]; Fluid pressure provides support: blue crab [74]; Pressure provides structural support: blackback land crab [74]	Reinforcement of foldable structures
Pulled support stalks have low flow stress: algae [25, p. 437; 66]	Construction
Intricate silica architecture ensures mechanical stability under high tension: diatoms [75–77]	MEMS
Crystals and fibres provide strength, flexibility: bones [78]; Byssus threads resist hydrodynamic forces [79]; Silk used for various functions: spiders [80]; Teeth resist compression and tension: animals that chew [25, pp. 332–333]; Elastic ligament provides support, shock absorption: large grazing mammals [25, p. 304]	Tough materials
Circular, tapering beams stabilize: plants [60]; Buttressing resists uprooting: English oak [25, pp. 431–432]; Resisting shearing forces: limpets [25, p. 427]; Variable postures aid intertidal zone survival: sea palm [25, p. 435]; Leaves resist gravitational loading: broad-leaved trees [25, p. 375]; Tentacles maintain tension as flow increases: marine polychaete worm [81]	Stabilize materials
Curved spine deals with tension: sloth [52, p. 37]; Low-energy perching: mousebird [82, pp. 240–241]	Tension resistant materials

are lost forever, before we even have started to value them. Gebeshuber and co-workers have recently proposed a niche tourism concept for Malaysia and Thailand, where corporate tourists and local bioscouts practice biomimetics in rainforests, coastal and marine environments and thereby provide sustainable usage of pristine tropical environment, increased income and employment in the host countries while encouraging conservation and sustainable tourism development [31, 32].

3.4.1 Application of the Biomimicry Innovation Method Concerning Mechanical Wear

Wear concerns the erosion of material from a solid surface by the action of another surface. It is related to surface interactions and more specifically the removal of material from a surface as a result of mechanical action. The need for

Table 3.6 Application of the BIM regarding buckling, fatigue and fracture (rupture)

Function	Biologized question: How does nature . . .	Nature's best practice	Generated process/ product ideas
Buckling	Stems resist buckling: bamboo and other plants [83, 25, p. 378]; Quills resist buckling: porcupine [84]; Siliceous skeleton provides support: Venus flower basket [85]; Shape of feather shafts protect from wind: birds [25, p. 385]; Crystals and fibres provide strength, flexibility: bones [59, p. 32–33; 78]; Organic cases provide protection: bagworm moths [86]; Bones absorb compression shock: birds [52, p. 39]; Leaves resist bending: trees [25, p. 580]; Skeleton provides support: sponges [25, p. 439]; Flexural, torsional stiffness with minimal material use: organisms [25, p. 440]; Spines work as shock absorbers: West European hedgehog [87]; Stems vary stiffness: scouring horsetail [88]		Bioinspired buckling resistant scaffolds
Fatigue	Plants survive repeated drying and rehydration: lesser clubmoss [89]; Wood resists fracture: trees [25, p. 343]; Pulled support stalks have low flow stress: algae [25, p. 437; 66]; Thin 'shells' resist impact loading: sea urchins [25, p. 388; 90–92]; Wings fold multiple times without wear: beetles [56]		Bioinspired fatigue resistant materials
Fracture (rupture)	Bones self-heal: vertebrates [70]; Iron sulphide minerals reinforce scales: golden scale snail [93]; Insect elytra resist shear and cracking: beetles [64]; Tendons and bones form seamless attachment: Chordates [94]; Leaves resist tearing: brown algae [59, pp. 35–36]; Microscopic holes deter fractures: starfish [25, p. 338–339]; Spicules help resist fractures: sponges [25, p. 337]; Extensibility helps stop spread of cracks: macroalgae [25, p. 338; 34, 95]; Shell resists cracking: scallop [25, pp. 339–340]; Leaves resist crosswise tearing: grasses [25, p. 340]; Antlers resist fracture: mammals [25, p. 349]; Resin protects damage: conifer trees [38]; Crystals and fibres provide strength, flexibility: bones [78]; Arterial walls resist stretch disproportionately: cephalopods [25, pp. 7–8]; Hooves resist cracking: horse [96, 97]; Continuous fibres prevent structural weakness: trees [98]; Ctenoid scales form protective layer: bony fish [52, p. 86]; Leaves resist bending: trees [25, p. 580]; Flexural, torsional stiffness with minimal material use: organisms [25, p. 440].		Bioinspired fracture resistant materials

mechanical action, in the form of contact due to relative motion, is an important distinction between mechanical wear and other processes with similar outcomes (e.g. chemical corrosion) [33]. Table 3.3 summarizes the application of the BIM regarding mechanical wear.

Table 3.7 Application of the BIM regarding deformation

Biologized question: How does nature …	Nature's best practice	Generated process/product ideas
… manage changes in humidity?	Plants survive repeated drying and rehydration: lesser clubmoss [10, p. 476]	Humidity resistant materials
… build stable scaffolds?	Crystals and fibres provide strength, flexibility: bones [59, pp. 32–33; 78]; Venus blower basket [85]	Scaffold in tissue engineering
… protect soft parts against deformation?	Skin properties derive from arrangement of components: mammals [99]	Mechanical protection (e.g. food packaging)
… provide mechanical stability?	Thin 'shells' resist impact loading: sea urchins [25, p. 388; 90–92]	Hard coated materials

Table 3.8 Application of the BIM regarding permanent attachment

Function	Nature's best practice	Generated process/ product ideas
Permanent adhesion via mechanical attachment	Diatom chains [13, 50, 71, 76]	Hinges and interlocking devices in micromachinery produced via rapid prototyping
Permanent adhesion via wet adhesives	Sticky proteins serve as glue: mammals [102]; Tendons and bones form seamless attachment [63, 78]; Anchor has flexibility: bull kelp [34]; Leaves glued together: grass trees [102]; Mucus glues sand and rock: marine worms [52, pp. 32–33]; Sticky proteins serve as glue: blue mussel [67]; Sticky berries adhere: European mistletoe [103]; Tendrils stick to various surfaces: Virginia creeper [104]; abalone shells [105]	Novel adhesives that can be produced in ambient conditions [106]
Permanent adhesion underwater via wet adhesives	Benthic diatoms [50, 71, 107]	Chemically stable underwater adhesives
Permanent adhesion via cement-like material	Eggs attached securely to hairs with a cement like substance: body lice [108]; Durable casing built with sand: protozoan's [109]; Termite faecal cement [110]	Cement produced at ambient conditions
Permanent adhesion via fluid substances that harden in air or water	Adhesive glues prey: velvet worms [36, p. 78]; Saliva used as glue: swifts [82, p. 239]; Threads adhere underwater: sea cucumber [111]	Novel two component adhesives

Table 3.9 Application of the BIM regarding temporary attachment

Temporary adhesion via mechanical attachment devices	Macro to milliscale: spinal column has strength and flexibility: armored shrew (macro) [82, p. 304]; Tendrils enable upward climb: rattan palm [112]; Adhering to multiple substrates: blackberry [57, p. 11]	Velcro analogues with no need for counterparts; novel structures and materials for hanging constructions; novel actuators; attachment of fragile structures	t9.1
	Microscale: special tongue captures soft prey: long-beaked echidna (*Tachyglossus* = swift tongue; *aculeatus* = furnished with spines) [113]; Insects with two pairs of wings have them work in unison by attaching the wings in various ways, with hooks, folds or catches [114]; Design features aid efficient attachment: lice [115]; Feet grip waxy leaves: leaf beetle [116]; Running on waxy leaves: Arboreal ants [25, p. 430; [117]		t9.2
	Nanoscale: biological attachment devices from the micro to the nano range [118]		t9.3
Temporary adhesion via dry adhesives	Gecko [119, 120]	Dry adhesives [121]	t9.4
Temporary adhesion via wet adhesives	Mucus takes on adhesive qualities: dusky arion slug [122]; Capillary action aids adhesion: European blowfly [123, 124]; Feet adhere temporarily: aphids [125]	Novel wet adhesives	t9.5
Temporary adhesion underwater via wet adhesives	Eggs adhere in and out of water: midwife toad [126]; Parasite attaches underwater: copepod [127]; Glue sticks underwater: giant water bug [126, p. 52]; motile diatoms [128]; Adhesive works under water: an aquatic bacterium (nature's strongest glue) [129]	Adhesives that can cure underwater	t9.6
Temporary adhesion in fluid conditions via switchable adhesives	White blood cells adhere closely: mammals [130]; White blood cells roll and stick: mammals [131]; Sticky berries adhere: European and Australian mistletoe [57, pp. 229–231; 103];	Switchable adhesives (release after signal, adapt binding strength to signal)	t9.7
Mixed	Feet of insects adjust to rough or smooth surfaces by engaging either claws or adhesive foot-pads [115]; Hooks and silk pads aid underwater attachment: blackfly [54, pp. 116–117]; Keyhole limpets attach using either suction or glue-like adhesion [132]; Barnacle cyprids employ wet and dry adhesion [133]; Disk-like structures adhere to smooth surfaces: Spix's disk-winged bat (Stefan and capillary adhesion) [25, p. 427]; Feet grip waxy leaves: leaf beetle [116, 134]; Multiple component glue aids underwater adhesion: barnacle [135]	Bioinspired reversible wet/dry adhesives [136]	t9.8

The lubrication strategies applied in chameleon tongues could for example be investigated regarding lubrication in bionanotechnological devices and fast actuators.

> 'The chameleon's tongue moves at ballistic speeds – the acceleration reaches 50 g – five times more than an F16 fighter jet. The burst of speed is produced by spiral muscles in the tongue, which contract width-wise to make them stretch forward. A lubricant allows the muscles to slide at time-slicing speeds.' [36, p. 70].

At the core of a chameleon's tongue is a cylindrical tongue skeleton surrounded by the accelerator muscle. High-speed recordings of *Chamaeleo melleri* and *C. pardalis* reveal that peak powers of 3,000 W/kg are necessary to generate the observed accelerations. The key structure in the projection mechanism is probably a cylindrical connective-tissue layer, which surrounds the entoglossal process and acts as lubricating tissue. Thus, the chameleon utilizes a unique catapult mechanism that is very different from standard engineering designs [58]. Industrial sectors interested in this strategy could be manufacturing, food and medicine; possible application ideas comprise bio-friendly lubrication for use in industry and actuators that lengthen quickly.

3.4.2 Application of the Biomimicry Innovation Method Concerning Shear

Shear concerns a deformation of an object in which parallel planes remain parallel but are shifted in a direction parallel to themselves. In many man-made materials, such as metals or plastics, or in granular materials, such as sand or soils, the shearing motion rapidly localizes into a narrow band known as a shear band. In that case, all the sliding occurs within the band, while the blocks of material on either side of the band simply slide past one another without internal deformation. A special case of shear localization occurs in brittle materials when they fracture along a narrow band. Then, all subsequent shearing occurs within the fracture. Table 3.4 summarizes the application of the BIM regarding shear.

3.4.3 Application of the Biomimicry Innovation Method Concerning Tension

Tension is the magnitude of the pulling force exerted by a string, cable, chain or similar object on another object. It is the opposite of compression. Tension is a force and is always measured parallel to the string on which it is applied. Table 3.5 summarizes the application of the BIM regarding tension.

3.4.4 *Application of the Biomimicry Innovation Method Concerning Buckling, Fatigue, Fracture (Rupture) and Deformation*

Buckling, fatigue, fracture (rupture) and deformation are well-known phenomena; their specific meaning in tribology is summarized below. *Buckling* is a failure mode characterized by a sudden failure of a structural member subjected to high compressive stresses, where the actual compressive stress at the point of failure is less than the ultimate compressive stresses that the material is capable of withstanding. This mode of failure is also described as failure due to elastic instability. Mathematical analysis of buckling makes use of an axial load eccentricity that introduces a moment, which does not form part of the primary forces to which the member is subjected. *Fatigue* is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The maximum stress values are less than the ultimate tensile stress limit, and may be below the yield stress limit of the material. *Fracture* mechanics is an important tool in improving the mechanical performance of materials and components. It applies the physics of stress and strain, in particular the theories of elasticity and plasticity, to the microscopic crystallographic defects found in real materials to predict the macroscopic mechanical failure of bodies. *Rupture* or ductile rupture describes the ultimate failure of tough ductile materials loaded in tension. Rupture describes a failure mode in which, rather than cracking, the material ‘pulls apart’, generally leaving a rough surface. *Deformation* denotes a change in the shape or size of an object due to an applied force. Tables 3.6 and 3.7 summarize the application of the BIM regarding buckling, fatigue and fracture (rupture); and deformation. The biologized question ‘How does nature manage changes in humidity?’ (Table 3.7, top) is a question resulting from reverse engineering, because we already know that shape change in nature is often initiated by changes in humidity.

3.4.5 *Application of the Biomimicry Innovation Method Concerning Attachment*

To stay put is important for many organisms; a plenitude of different methods for mechanical attachment or chemical bonding had been evolved. In this book chapter, mechanisms to stay put are divided in to mechanisms for permanent and temporary attachment.

Permanent adhesion can occur via mechanical attachment. One intriguing example for this on the small scale is diatom chains with hinges and interlocking devices that are just some hundreds of nanometers large and that connect the single celled organisms to chains. Some of these connections (still functional) can be found in fossils of diatoms that lived tens of millions of years ago [100]. Most man-made adhesives fail in wet conditions, owing to chemical modification of the adhesive or its substrate. Therefore, bioinspiration from natural underwater adhesives is very much in need. The adhesive that *Eunotia sudetica*, a benthic freshwater diatom species, produces to attach itself to a substrate has for example modular, self-healing properties [50]. Another class of adhesives comprises cement-like materials and adhesives that dry in air. Dry adhesives as they occur in the gecko have been thoroughly investigated, and currently first man-made bioinspired gecko adhesives are produced [101]. Tables 3.8 and 3.9 summarize the application of the BIM regarding permanent and temporary attachment, respectively. In Table 3.9, the mechanical attachment devices for the temporal attachment are structured according to their size (millimetres and above, micrometres and nanometres) – this should help prevent problems with any scaling effect when doing the technology transfer from biology to technology.

Climbing palms, such as the highly specialized rattan palms in the Southeast Asian rainforests, evolved leaves armed with hooks and grapnels for climbing (Fig. 3.5). Some species of rattan palms develop a climbing organ known as the flagellum, which also bears hooks. The leaves are constructed to optimize bending and torsion in relation to the deployment of re-curved hooks. It is a joint phenomenon that hooks in organisms increase in strength toward their base, and that the hooks always fail in strength tests before the part of the organism they are attached to. The sizes and strengths of the hooks differ between species and are related to body size and ecological preference. Larger species produce larger hooks, but smaller climbing palms of the understory deploy fine sharp hooks that are effective on small diameter supports as well as on large branches and trunks. Climbing organs in palms differ significantly from many vines and lianas having more perennial modes of attachment [137].

Fig. 3.5 Details of the climbing palm rattan. The hooks protect the plant against predators and assist in climbing and growing through the understory in the tropical rain forests. Image reproduced with permission, © F. Saad, IPGM, Malaysia

> 'The front tip, from which all growth comes, explores with extremely long, thin tendrils equipped along their length with needle-sharp curved hooks. If these snag your arm – and the tendrils are so thin that they can easily be overlooked – they can rip both your shirt and your flesh. With these, it hitches itself on to an established tree and actively grows upwards. Sometimes the support is not strong enough to bear the extra load and it collapses, but the rattan is not deterred. It continues to grow as it sprawls across the forest floor and does so with such vigour that some species develop longer stems than any other plant and may reach a length of over five hundred feet.' [57, pp. 162–163]

Bioinspired products and application ideas comprise fasteners, clips, snaps, slide fastener tapes and a novel Velcro analogue (possibly noiseless!) with no need for a counterpart.

3.5 Summary and Outlook

This chapter presented 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 shall be performed, and the underlying principles shall be extracted. Such principles shall then be incorporated into devices, systems and processes and thereby yield biomimetic technology with increased tribological performance.

To accelerate scientific and technological breakthroughs, we should aim at having a context of knowledge: the gap between scientific insights and technological realization should be bridged [138]. Especially in a field which is as application-oriented as biomimetics related to tribology, care has to be taken that the scientific findings actually can lead to real-world applications. As Gebeshuber and co-workers outlined in 2009 [1] in their 'three gaps theory', there are gaps between inventors, innovators and investors (see Fig. 3.6). 'Inventor gap' denotes the gap between

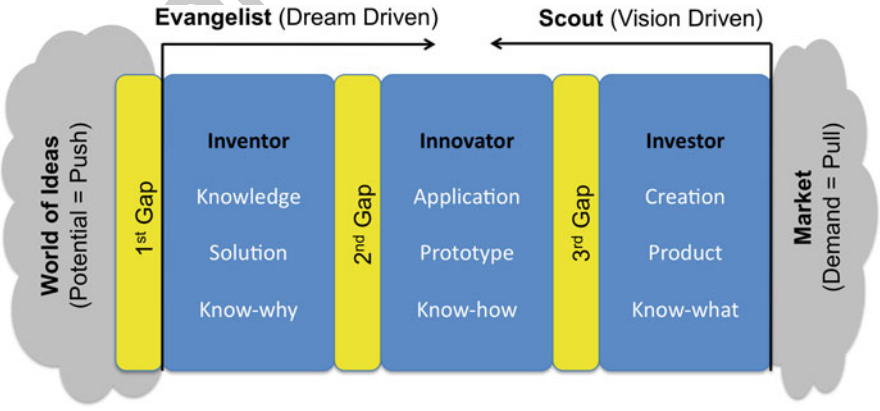

Fig. 3.6 The three gaps theory regarding inventors, innovators and investors. ©2009 PEP Publishing, London. Reproduced from [1] with permission

knowing and not knowing that has to be overcome to have ideas. The 'innovator gap' denotes the gap between knowledge and application of the knowledge. The 'investor gap' denotes the gap between the application and the creation of the product. To prevent being trapped in the inventor, innovator or investor gap, a cross dialogue is necessary, a pipeline from 'know-why' to 'know-how' to 'know-what', from the inventor who suggests a scientific or technological breakthrough to the innovator who builds the prototype to the investor who mass produces the product and brings the product to the consumer. Currently, and this is a major problem, at universities worldwide huge amounts of knowledge are piled up with little or no further usage. We know a lot, we can do relatively little. We need a joint language and a joint vision. This is specifically of relevance in tribology, since tribological research is ultimately linked to real-world applications. Applying biomimetics to tribology could provide such a pipeline.

On the basis of the long-standing experience of research at the interface between tribology and biology [e.g. 2, 8, 12, 13, 14, 100], Gebeshuber and co-workers recently introduced a concept for a dynamic new way of scientific publishing and accessing human knowledge [138]. The authors propose a solution to the dilemma that a plenitude of biology papers that deal with friction, adhesion, wear and lubrication were written solely for a biology readership and have high potential to serve as inspiration for tribology if they were available in a language or in an environment accessible for tribologists (cf. Figs. 3.2 and 3.3). The British publishing house Professional Engineering Publishing will host the first scientific journal that aims at turning the dynamic publishing concept into reality. The editor of this new journal, who is one of the authors of this chapter, ICG, will thereby get the chance to possibly revolutionize the way we are doing science, and contribute to overcoming the gaps between inventor, innovator and investor, by presenting and managing research results in a way that is accessible by people with different kinds of backgrounds and levels of education.

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Living in the tropics and continuous exposure to high species diversity in the tropical rainforests is a highly inspirational way to continuously do biomimetics. Researchers have the current problems they are dealing with always at the back of their head, and an inspiring environment aids in developing completely new ideas, approaches and concepts. The Vienna University of Technology, especially Profs. F. Aumayr, H. Störi and G. Badurek, are acknowledged for enabling one of the authors (ICG) three years of research in the inspiring environment in Malaysia.

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