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Preface

This 6th Plant Biomechanics conference is hosted by French Guiana, a tiny part of the huge Amazonian forest, on the Guyana shield. French Guiana was a place where tree biomechanics research begins in the seventies in a close cooperation between French and Japanese scientists. Many participants to this conference made part of their work here in French Guiana and it is a pleasure to make the other discover this wonderful tropical rain forest.

As for the former conferences there will be papers dealing with all kind of plants and very different mechanical solutions at whole plant, organ or cell level. There is also a strong emphasis on useful material coming from plants and on bio-inspired solutions for engineering.

Some participants, old friends of the beginning, were actors of the five other PBM, but many young scientists and PhD come for the first time and this is good news for the future of our community. It is a pity that some of us cannot participate this time because of fund restrictions due to the economic crisis but they keep in contact and we will send them the proceedings of this conference.

I want to mention all the national or regional organizations that help us for the funding and the organization of PBM 2009, namely, AgroParisTech, CIRAD, CNES, CNRS, INRA, DRRT Guyane, IESG, IRISTA, IUFM, PUG, Région Guyane and UAG.

I want also to give a very special thank to Laetitia and Julien Ruelle. Without the energy of Laetitia this conference will not have been possible and without the expertise of Julien, these proceedings will not be under your eyes.

Thanks also to all the colleagues and PhD students who were there when needed for so many help in such an adventure.

And last, thanks to the members of the scientific committee for their reactivity and efficient reviewing of the text here after.

Have a good reading.

Bernard THIBAUT
Directeur de recherche au CNRS
Directeur de l'UMR Ecofog

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Exploring the innovation potential of biomimetics for novel 3D micro- and nanoelectromechanical systems (MEMS and NEMS)

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Abstract

Science currently goes through a major change, with biology gaining increasing importance. A new Leitwissenschaft that can be called “Biological Physics“ is evolving. Biomimetics, i.e., technology transfer from biology to engineering, is especially promising in MEMS development because of the material constraints in both fields. Biomimetic concepts such as integration instead of additive construction, optimization of the whole instead of maximization of a single component feature, multi-functionality instead of mono-functionality and development via trial-and-error processes can also be applied by engineers not at all involved in biology.

A novel way to describe the complexity of biological and engineering approaches depending on the number of different base materials is proposed: Either many materials are used (*material* dominates) or few materials (*form* dominates) or just one material (*structure* dominates). The complexity of the approach (in biology as well as in engineering) increases with decreasing number of base materials. Biomimetics is a field that has the potential to drive major technical advances and that continuously contributes to “Biological Physics”.

The Biomimicry Innovation Method is applied to identify high-potential biological systems, processes and materials that can inspire emerging MEMS technologies as well as optimizing existing ones. Best practices identified comprise algae, horses, Malaysian tropical rainforest understory plants, iridescent fruits, peacock feathers, bird skin, green algae, humans (immune system), adhesive pads in the gecko and in herbivorous insects as well as the mechanical defense strategies of their food.

Introduction

In biomimetics, materials, processes and systems in Nature are analyzed, the underlying principles are extracted and subsequently applied to science and technology [1][2][3]. Biomimetics is a growing field that has the potential to drive major technical advances [4]. It might substantially support successful mastering of current challenges in the development of novel 3D micro- and nanoelectromechanical systems (MEMS and NEMS), e.g., concerning friction, adhesion and wear in such systems (tribological aspects) [5]. The biomimetic approach can result in innovative new technological constructions, processes and developments [3]. Biomimetics can aid MEMS developers to manage the specific requirements in systems or product design, which are even more relevant than for conventional products, especially to create products and processes that are sustainable and perform well (e.g. to overcome stiction), 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 [6][7][8][9].

Recurrent principles in biological materials and systems are hierarchy [10][11] and multi-functionality. Vincent and co-workers analyzed 500 biological phenomena, covering over 270 functions, at different levels of hierarchy [10]. Depending on the extent to which each level of the hierarchy is dependent on its lower levels, adaptation or optimization of the biomaterial is independently possible at each level of hierarchy. Size differences between hierarchy levels tend to be about a factor of ten [11]. A major advantage of hierarchical structuring is that the material can be made multifunctional and that a specific material property, such as fracture toughness, can be improved by optimization at different size levels. A direct consequence is the increase in adaptability of natural materials. Functions can be modified or enriched by structuring on an additional level of hierarchy. Adaptability increases, therefore, as a function of the number of levels of hierarchy. This is probably why such a wide range of material and structural properties (see Figure 1 for biological SiO_2 structures in glass-making microorganisms, [7]) can be provided in Nature by such a small range of base materials [12][13].

Biological materials show excellent characteristics that are difficult to grasp in terms of commonly used material properties such as resilience (a component of ecosystem stability: the ability of an ecosystem to recover after disturbance) [14][15][16], self-repair [17], adaptability [16], benevolent behavior [18] and redirected crack propagation [19][20].

Structure and function as well as structure and material are closely related in natural systems. Gordon [21] states "*Structures are made from materials and we shall talk about structures and materials; but in fact there is no clear-cut dividing line between a material and a structure.*" Historically interested readers might also want to read Haeckel's book "Art forms in nature" [22] and D'Arcy Thompson's book "On Growth and Form" [23], especially chapters V on biomineralized structures and VIII on form and mechanical efficiency. Investigations on the cause of the excellent properties of natural materials lead to investigations of intrinsic material properties.

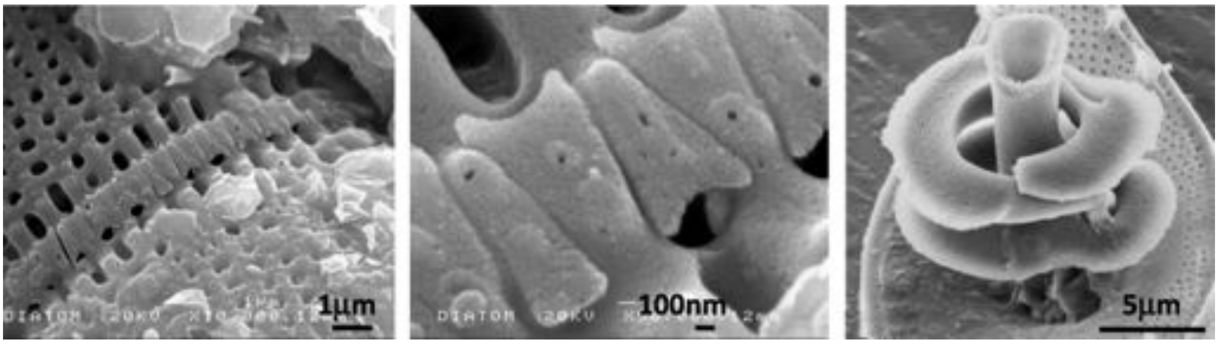

Fig. 1 Structure dominated micromechanical components (SiO_2 shells of algae). Left: Zipper-like structure in Aulacoseira. Middle: Zoom into the same image. © Duncan Waddell, XTAL Enterprises, Australia. Right: Spring-like structure in Rutilaria grevilleana. © R.M. Crawford, AWI Bremerhaven, Germany. Images used with permission. From [7].

Science currently goes through a large change: in biology more and more causation and natural laws are being uncovered [24]. Biology has changed from being very descriptive to a science that can be acknowledged and understood (in terms of concepts) by researchers coming from "hard sciences" such as chemistry, physics, engineering. The "hard sciences" rely on experimental, empirical, quantifiable data or the scientific method, and focus on accuracy and objectivity [25]. The amount of causal laws in this new biology (indicated by the ratio of causal versus descriptive knowledge, Figure 2) is steadily growing and a new field that can be called "Biological Physics" is emerging [24]. 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.

Recurrent concepts in biomimetics are integration instead of additive construction, optimization of the whole instead of maximization of a single component feature, multi-functionality instead of mono-functionality and development via trial-and-error processes. Such concepts can easily be transferred to technology, and can be applied by engineers with no knowledge of biology at all [3][9][24].

The complexity of biological and engineering approaches depend on the number of different base materials used (Figure 3): Either many materials are used (*material* dominates) or few materials (*form* dominates) or just one material (*structure* dominates) [7].

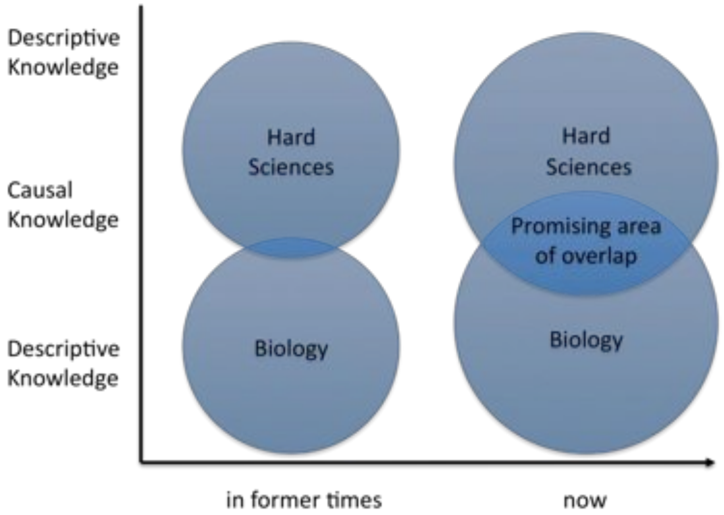

Fig. 2 The increasing amount of causal laws in biology generates promising areas of overlap with hard sciences such as physics, chemistry and engineering.

The importance of structures and the complexity of the approach (in biology as well as in engineering) increase inversely with the number of different materials that are or can be used. This can be seen in technology from the meter to the nanometer length scale. The Eiffel tower, e.g., which is mainly made from steel, has many levels of structural hierarchy with important structures on every length scale [7].

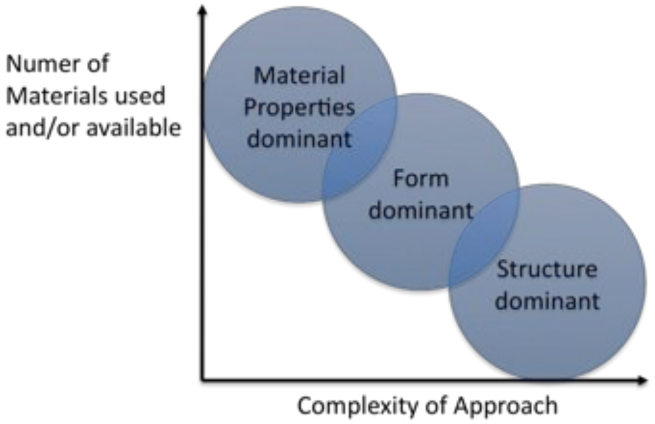

Fig. 3 The complexity of biological and engineering approaches depends on the number of different base materials used and/or available.

Material and methods

In MEMS and NEMS technology – comparable to biology - a limited number of base materials such as Si, SiO_2, Silicon nitride, GaAs, Silicon carbide, diamond, InP, SiGe, ferroelectric materials and polymers is used, providing a wide range of functional and structural properties. Therefore, biomimetics seems to prove especially promising for MEMS development [7].

Nachtigall promoted analogy search and states that the nature of qualitative analogy research is impartial, open-minded comparison. He presents numerous examples of insect micromorphology and relates functional mechanisms to technological examples in a visual comparison [26].

Here, the Biomimicry Innovation Method (BIM) [27] is applied to identify high-potential biological systems, processes and materials that can inspire emerging MEMS technologies as well as optimizing existing ones. BIM is an innovation method that 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. BIM involves specifically trained biologists as well as engineers, natural scientists, architects and/or designers from universities or companies. BIM is for example used in the rainforest (high species variety resulting in high innovation potential) to learn from and emulate natural models.

Table 1 Application of the Biomimicry Innovation Method regarding structure dominated components

Function	Biologized question: **How does nature …**	**Nature's best practice**	Generated process/ product ideas
Hinges and interlocking devices	… mechanically connect hard single cells?	Diatoms in chains [28][29][30][31][32][33]	micromechanical optimization of 3D-MEMS structure
Click-stop mechanism	… unfold structures and then fix them?	*Corethron pennatum, C. criophilum* [29][34][35]	obtain 3D structures from 2D structures
Springs	… reversibly store mechanical energy?	*Rutilaria grevilleana, R. philipinnarum* [36]	Energy storage in MEMS
Parts connected in a chain with adjustable length	… provide stability to chains in turbulent environments?	*Ellerbeckia arenaria* [32]	MEMS with moveable parts
Movable rigid parts	… optimize moveable parts?	*Melosira sp., Ellerbeckia arenaria* [32]	3D MEMS with moveable parts
Pumps	… move fluids?	*Rutilaria grevilleana, Rutilaria philipinnarum* [36]	micropumps for lab-on-a-chip
Unfoldable structures	… make 3D structures from rigid parts?	*Corethron pennatum, C. criophilum* [29][34][35]	obtain 3D structures from 2D structures
Energy dissipation	… dissipate mechanical energy?	*Solium exsculptum* [5][37]	3D-MEMS
Fracture control, Crack redirection	… mechanically protect viable parts?	*Equus ferus caballus* [19][20]	quality assurance of MEMS
Lubrication	… prevent wear?	Unknown diatom species [33]	preventing stiction
Stability (reinforcement)	… mechanically protect viable parts?	*Solium exsculptum* [5][37]	quality assurance of MEMS
Surface texturing	… structure surfaces?	diatoms [28], especially *Solium exsculptum* [5][37]	MEMS
Photoprotective coating	… protect photo-sensitive plants?	*Begonia pavonina, Diplazium tomentosum, Phyllagathis rotundifolia* [38], *Selaginella willdenowii, S. uncinata* [39]	MEMS
Photonic components	… make colours without pigments?	diatoms [28], feathers [40], butterflies and moths [41][42], iridescent plants [38][39][43] [44][45] [46][47][48][49], bird and mammal skin [50][51] [52], iridescent marine algae [53][54], blue spruce [55]	photonic micro- and nanodevices, MEMS
Pressure resistant containers	… deal with high pressures?	*Euglena gracilis* pellicle [56]	lab-on-a-chip
Fixation	… mechanically fix structures?	*Corethron pennatum, C. criophilum* [29][34][35]	3D-MEMS, lab-on-a-chip
Selective, switchable adhesion	… reversibly and switchable adhere to structures?	*Homo sapiens sapiens* immune system [5][31][57][58][59]	reusable lab-on-a-chip devices [60]
Dry adhesives	… reversibly attach to surfaces?	gecko foot [61][62], insect attachment pads [63][64], plant wax surfaces [65][66]	connect MEMS parts, nanoadhesives [67][68]
Self-healing adhesives	… prevents breaking of adhesive bonds?	self-healing diatom adhesives [69][70][71]	self-healing MEMS parts connections, nanoadhesives [72]

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 mechanically connect hard single cells?" or "How does Nature generate 3D structures from rigid parts?" The basic question is "What would Nature do here?" The experience of one of the authors (ICG) on the boundary between biology and engineering, literature search, talks with experts from biology and the AskNature.org database provided by the Biomimicry Institute are utilized in course of the BIM to exploit the large biodiversity in rainforests and in the water bodies of the world and to find biological inspiration for functions relevant for MEMS such as click-stop mechanisms, micropumps, energy dissipation and lubrication (Table 1).

Find Nature's best practices: Screens of the relevant literature in scientific databases as well as entering a highly inspiring environment with the biologized questions in mind (task-oriented visit) are used to obtain a compendium of how plants, animals and ecosystems solve the specific challenge. The inspiring environments should preferably be habitats with high species diversity, e.g., the rain forest or a coral reef. Thereby a compendium of how plants, animals and ecosystems solve the specific challenge is obtained.

Generate process/product ideas: From these best practices (90% of which are usually new to clients) ideas for cost-effective, innovative, life-friendly and sustainable products and processes are generated.

Results and discussion

The best practices identified are biological micro- and nanostructures in organisms as diverse as algae, horses, Malaysian tropical rainforest understory plants, peacocks, birds, green algae, humans (immune system), adhesive pads in the gecko and in herbivorous insects as well as the mechanical defense strategies (wax crystals) of their food. The summary of the results is given in Table 1.

The organisms that occur most often in the table are diatoms. Diatoms are unicellular microalgae with a cell wall consisting of a siliceous skeleton enveloped by a thin organic case [28]. The cell walls of each diatom form a pillbox-like shell consisting of two parts that fit within each other. These microorganisms vary greatly in shape, ranging from box-shaped to cylindrical; they can be symmetrical as well as asymmetrical and exhibit an amazing diversity of nanostructured frameworks. These biogenic hydrated silica structures have elaborate shapes, interlocking devices, and, in some cases, hinged structures.

The silica shells of the diatoms experience various forces from the environment and also from the cell itself when it grows and divides, and the form of these micromechanical parts has been evolutionarily optimized during the last 150 million years or more (Figure 1). The diatom species *Rutilaria grevilleana* and *Rutilaria philipinnarum* have structures that might be interpreted as springs [7][36]. However, more detailed investigation is needed to confirm this. *Ellerbeckia arenaria* [73] is a diatom that lives in waterfalls. *E. arenaria* cells form string like colonies, which can be several millimeters long and can reversibly be elongated by one third of their original length [32][37][7]. The diatoms *Melosira sp.* [32], *Solium exsculptum* [5][4] and *Ellerbeckia arenaria* are interesting best practices for optimization of moveable parts in Nature. The diatom species *Solium exsculptum* lived 45 million years ago. Scanning Electron Microscopy images of this Eocene fossil from a deposit at Mors, Denmark reveal that the connections between sibling cells are still in good condition [5].

Rutilaria philipinnarum is a fossil colonial diatom thought to have lived in inshore marine waters (Crawford, personal communication 2008). In this species, the single diatoms connect by linking spines and by a complex siliceous structure termed the periplekton. These linking structures on the one hand keep the cells together, but on the other hand also keep distance between the cells. The shape of the spines allows expansion of the chain to a certain maximum distance and compression to a minimum distance, in which case there is still some fluid between the cells. The links allow movement of single cells in the chain against or from each other in a rather one-dimensional way [29].

Structural photonic components in biology exhibit a huge variety [28][40]-[42][38][39][43]-[55].

Conclusion

Application of the Biomimicry Innovation Method concerning 3D micro- and nanomechanical systems might prove highly useful concerning MEMS development. The inspiring organisms, structures and function already identified lay a sound foundation to proceed to the next step: MEMS developers interested in including the bioinspired approaches presented in this work have already been approached and bioinspired 3D MEMS will be designed and modeled and prototypes will be constructed. Further analysis of the rich flora in South East Asia might provide further useful input concerning novel approaches regarding MEMS. Increasing awareness about the innovation potential of the rainforest might cause a paradigm shift in the way locals view the pristine forests.

Acknowledgements

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This book chapter is an extended and updated version of a 4-page article [7].

References

1. Bhushan, B. (2009): *Biomimetics: lessons from nature-an overview.* Philosophical Transactions of the Royal Society A. 367: 1445-1486.
2. Bar-Cohen, Y. (2005): *Biomimetics: biologically inspired technologies*, CRC Press.
3. Gebeshuber, I.C. and M. Drack, (2008): *An attempt to reveal synergies between biology and engineering mechanics.* Journal of Mechanical Engineering Science. 222, 1281-1287.
4. Gebeshuber I.C., Majlis B.Y. and Stachelberger H. (2009): *Tribology in Biology: Biomimetic studies across dimensions and across fields.* International Journal of Mechanical and Material Engineering, submitted
5. Gebeshuber, I.C., (2007): *Biotribology inspires new technologies.* Nano Today. 2(5): 30-37.
6. Gebeshuber, I.C., A. Pauschitz and F. Franek. (2006): *Biotribological model systems for emerging nano-scale technologies*, in: Proc. 2006 IEEE Conference on Emerging Technologies - Nanoelectronics, Editors, p. 396-400.
7. Gebeshuber, I.C., Stachelberger H., Ganji B.A., Fu D.C., Yunas J. and Majlis B.Y. (2009): *Exploring the innovational potential of biomimetics for novel 3D MEMS.* Advanced Materials Research. 74, 265-268.
8. Gebeshuber, I.C., H. Stachelberger and M. Drack. (2005): *Diatom tribology*, in: Life Cycle Tribology, Editors, Tribology and Interface Engineering Series, 48, Series Editor B.J. Briscoe, Elsevier, p. 365-370.
9. Gebeshuber, I.C., B.Y. Majlis, L. Neutsch, F. Aumayr and F. Gabor. (2009): *Nanomedicine and biomimetics: life sciences meet engineering & physics*, Proceedings of the 3rd Vienna International Conference on Micro- and Nanotechnology Viennano09, Editors, p. 17-23.
10. Fratzl, P. and R. Weinkamer, (2007): *Nature's hierarchical materials.* Progress in Materials Science. 52 (8), 1263-1334.
11. Vincent, J.F.V., (2005): *Deconstructing the design of a biological material.* Journal of Theoretical Biology. 236, 73-78.
12. Jeronimidis, G. and A.G. Atkins, (1995): *Mechanics of biological materials and structures—Nature's lessons for the engineer.* Proceedings of the Institution of Mechanical Engineers Part C: Journal of Mechanical Engineering Science. 209, 221-235.
13. Vincent, J.F.V., (2009): *Biomimetics – A review.* Proceedings of the Institution of Mechanical Engineers Part H: Journal of Engineering in Medicine, submitted
14. Holling, C.S., (1973): *Resilience and stability of ecological systems.* Annual Review of Ecological Systems. 4, 1-23.
15. *Resilience and the behavior of large-scale systems* (2002). Scope Report 60, Editors, Island Press.
16. Walker, B., C.S. Holling, S.R. Carpenter and A. Kinzig (2004): *Resilience, adaptability and transformability in social–ecological systems.* Ecology and Society. 9(2), 5.

17. *Proceedings of the first workshop on self-healing systems* (2002). Charleston, South Carolina.
18. Trivers, R.L. (1971): *The evolution of reciprocal altruism.* The Quarterly Review of Biology. 46(1), 35-57.
19. Kasapi, M.A. and J.M. Gosline, (1997): *Design complexity and fracture control in the equine hoof wall.* Journal of Experimental Biology. 200, 1639-1659.
20. Kasapi, M.A. and J.M. Gosline, (1999): *Micromechanics of the equine hoof wall: optimizing crack control and material stiffness through modulation of the properties of keratin.* Journal of Experimental Biology. 202, 377-391.
21. Gordon, J.E. (1981): *Structures, or why things don't fall down*, Da Capo Press New York. p. 29.
22. Haeckel E. (1899): *Art forms in nature.* Biobliographisches Institut, Leipzig and Vienna.
23. Thompson D'A. (1917): *On growth and form.* Cambridge University Press, Cambridge, England.
24. Gebeshuber, I.C., P. Gruber and M. Drack, (2009): *A gaze into the crystal ball - biomimetics in the year 2059.* Proceedings of the Institution of Mechanical Engineers Part C: Journal of Mechanical Engineering Science, submitted
25. Lemons, J., (1996): *Scientific uncertainty and its implications for environmental problem solving*, Blackwell Publishing.
26. Nachtigall, W., (2003): *Das große Buch der Bionik.* Deutsche Verlagsanstalt, Germany, p. 214f.
27. *Biomimicry innovation method* (2008). Biomimicry Guild, Helena, MT, USA.
28. Round, F.E., R.M. Crawford and D.G. Mann (1990): *The diatoms: biology and morphology of the genera.* Cambridge University Press, Cambridge, UK.
29. Gebeshuber, I.C. and R.M. Crawford, (2006): *Micromechanics in biogenic hydrated silica: hinges and interlocking devices in diatoms.* Journal of Engineering Tribology. 220(J8), 787-796.
30. Crawford, R.M. and I.C. Gebeshuber, (2006): *Harmony of beauty and expediency.* Science First Hand. 5(10), 30-36.
31. Gebeshuber, I.C., M. Drack and M. Scherge, (2008): *Tribology in biology.* Tribology - Materials, Surfaces & Interfaces. 2(4), 200-212.
32. Gebeshuber, I.C., H. Stachelberger and M. Drack, (2005): *Diatom bionanotribology - Biological surfaces in relative motion: their design, friction, adhesion, lubrication and wear.* Journal of Nanoscience and Nanotechnology. 5 (1), 79-87.
33. Gebeshuber, I.C., J.H. Kindt, J.B. Thompson, Y. Del Amo, H. Stachelberger, M. Brzezinski, G.D. Stucky, D.E. Morse and P.K. Hansma, (2003): *Atomic force microscopy study of living diatoms in ambient conditions.* Journal of Microscopy. 212 (Pt3), 292-299.
34. Crawford, R.M. and F. Hinz, (1995): *The spines of the centric diatom Corethron criophilum: light microscopy of vegetative cell division.* European Journal of Phycology. 30: 95–105.
35. Crawford, R.M., F. Hinz and C. Honeywill, (1998): *Three species of the diatom genus Corethron Castracane: structure, distribution and taxonomy.* Diatom Research. 13: 1–28.
36. Srajer, J., B.Y. Majlis and I.C. Gebeshuber, (2009): Microfluidic simulation of a colonial diatom chain reveals oscillatory movement. Acta Botanica Croatia, in press
37. Gebeshuber, I.C., M. Aumayr, O. Hekele, R. Sommer, C.G. Goesselsberger, C. Gruenberger, P. Gruber, E. Borowan, A. Rosic and F. Aumayr. (2009): *Bacilli, green algae, diatoms and red blood cells – how nanobiotechnological research inspires architecture*, in: Bio-Inspired Nanoscience, edited by Yong Zhou, Nova Science Publishers 2009, in press
38. Gould, K.S. and D.W. Lee (1996): *Physical and ultrastructural basis of blue leaf iridescence in four Malaysian understory plants.* American Journal of Botany. 83(1), 45-50.
39. Hebant C. and D.W. Lee, (1984): *Ultrastructural basis and developmental control of blue iridescence in Selaginella leaves.* American Journal of Botany. 71(2), 216-219.
40. Zi J., X. Yu, Y. Li, X. Hu, C. Xu, X. Wang, X. Liu and R. Fu, (2003): Coloration strategies in peacock feathers. Proceedings of the National Academy of Sciences USA. 100(22): 12576-12578.
41. Prum, R.O., T. Quinn and R.H. Torres, (2006): *Anatomically diverse butterfly scales all produce structural colours by coherent scattering.* The Journal of Experimental Biology. 209, 748-765
42. Stavenga, D.G., S. Stowe, K. Siebke, J. Zeil and K. Arikawa, (2004): *Butterfly wing colours: scale beads make white pierid wings brighter.* Proceedings of the Royal Society London B. 271, 1577-1584.
43. Lee, D.W. and J.B. Lowry, (1975): *Physical basis and ecological significance of iridescence in blue plants.* Nature. 254, 50-51.
44. Lee, D.W. (2007): *Nature's palette: the science of plant color.* University of Chicago Press, Chicago, USA.
45. Richards, P.W., (1952): *The tropical rainforest*, Cambridge University Press.
46. Fox, D.L. and J.R. Wells (1971): *Schemochromic blue leaf-surfaces of Selaginella.* American Fern Journal. 61, 137-139
47. Lee, D.W., (1977): *On iridescent plants.* Gardens Bulletin Singapore. 30, 21-29.

48. Lee, D.W. (1991): *Ultrastructural basis and function of iridescent blue colour of fruits in Elaeocarpus.* Nature. 349, 260-262.
49. Lee, D.W., G.T. Taylor and A.K. Irvine, (2000): *Structural fruit coloration in Delarbrea michieana (Araliaceae).* International Journal of Plant Sciences. 161(2), 297-300.
50. Fox, D. S. (1976): *Animal structural colors and biochromes.* University of California Press, Berkeley, USA.
51. Prum, R.O. and R. Torres, (2003): *Structural colouration of avian skin: convergent evolution of coherently scattering dermal collagen arrays.* The Journal of Experimental Biology. 206, 2409-2429
52. Prum, R.O. and R.H. Torres, (2004): *Structural colouration of mammalian skin: convergent evolution of coherently scattering dermal collagen arrays.* The Journal of Experimental Biology. 207, 2157-2172.
53. Gerwick, W.H. and N.J. Lang, (1977): *Structural chemical and ecological studies on iridescence in Iridaea (Rhodophyta).* Journal of Phycology. 13(2), 121-127
54. Pederson, M., G.M. Roomans and A. Hofsten, (1980): *Blue iridescence and bromine in the cuticle of the red alga Chondrus cripus Stackh.* Botanica Marina. 23, 193-196
55. Pfündel, E.E., G. Agati and Z.G. Cerovic (2006): *Optical properties of plant surfaces*, in Biology of the plant cuticle. Editors, Blackwell Publishing, Oxford, 23, p. 216-249.
56. Gruenberger, C., R. Ritter, F. Aumayr, H. Stachelberger and I.C. Gebeshuber, (2007): *Algal biophysics: Euglena gracilis investigated by atomic force microscopy.* Materials Science Forum. 555: 411-416.
57. Tees, D.F. and D.J. Goetz, (2003): *Leukocyte adhesion: an exquisite balance of hydrodynamic and molecular forces.* News in Physiological Sciences. 18, 186-190.
58. Orsello, C.E., D.A. Lauffenburger and D.A. Hammer, (2001): *Molecular properties in cell adhesion: a physical and engineering perspective.* Trends in Biotechnology. 19(8), 310-316.
59. Kawasaki E. and A. Player (2005): *Nanotechnology, nanomedicine, and the development of new, effective therapies for cancer.* Nanomedicine: Nanotechnology, Biology and Medicine. 1(2), 101-109.
60. Sakhalkar, HS, M.K. Dalal, A.K. Salem, R. Ansari, J. Fu, M.F. Kiani, D.T. Kurjiaka, J. Hanes, K.M. Shakesheff and D.J. Goetz, (2003): *Leukocyte-inspired biodegradable particles that selectively and avidly adhere to inflamed endothelium in vitro and in vivo.* Proceedings of the National Academy of Sciences USA. 100: 15895-15900.
61. Autumn, K., Y.A. Liang, S.T. Hsieh, W. Zesch, W.P. Chan, T.W. Kenny, R. Fearing and R.J. Full (2000): *Adhesive force of a single gecko-foot hair.* Nature. 405, 681-685.
62. Dubrow, R., (2003): *Structures, systems and methods for joining articles and materials and uses therefore.* US Patent 7056409
63. Scherge, M. and S. Gorb, (2001): Biological micro- and nanotribology – Nature's solutions. Springer Verlag, Berlin Heidelberg.
64. Gorb, E.V. and S.N. Gorb, (2002): A*ttachment ability of the beetle Chrysolina fastuosa on various plant surfaces.* Entomologia Experimentalis et Applicata. 105 (1), 13-28.
65. Gorb, E., K. Haas, A. Henrich, S. Enders, N. Barbakadze and S. Gorb, (2005): *Composite structure of the crystalline epicuticular wax layer of the slippery zone in the pitchers of the carnivorous plant Nepenthes alata and its effect on insect attachment.* Journal of Experimental Biology. 208, 4651-4662.
66. Koch, K. A. Dommisse, W. Barthlott and S.N. Gorb, (2007): *The use of plant waxes as templates for micro- and nanopatterning of surfaces.* Acta Biomaterialia. 3 (6), 905-909.
67. Northen, M.T. and K.L. Turner (2005): *A batch fabricated biomimetic dry adhesive.* Nanotechnology. 16 (8): 1159-1166.
68. Shah, G.J. and Sitti M. (2004): *Modeling and design of biomimetic adhesives inspired by gecko foot-hairs*, In: IEEE International Conference on Robotics and Biomimetics (ROBIO), p. 873-878.
69. Gebeshuber, I.C., J.B. Thompson, Y. Del Amo, H. Stachelberger and J.H. Kindt, (2002): *In vivo nanoscale atomic force microscopy investigation of diatom adhesion properties.* Materials Science and Technology. 18, 763-766.
70. Higgins, M.J., P. Molino, P. Mulvaney and R. Wetherbee, (2003): *The structure and nanomechanical properties of the adhesive mucilage that mediates diatom-substratum adhesion and motility.* Journal of Phycology. 39: 1181-1193.
71. Higgins, M.J., J.E. Sader, P. Mulvaney and R. Wetherbee, (2003): *Probing the surface of living diatoms with atomic force microscopy: the nanostructure and nanomechanical properties of the mucilage layer.* Journal of Phycology. 39, 722-734.
72. Hansma, P.K., P.J. Turner and R.S. Ruoff, (2007): *Optimized adhesives for strong, lightweight, damage-resistant, nanocomposite materials: new insights from natural materials.* Nanotechnology. 18, 044026(3p).
73. Schmid, A-M.M. and R.M. Crawford, (2001): *Ellerbeckia arenaria (Bacillariophyceae): formation of auxospores and initial cells.* European Journal of Phycology. 36: 307-320.

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