Bacilli, green algae, diatoms and red blood cells – how nanobiotechnological research inspires architecture

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Abstract

Biological processes, structures, functions and materials provide powerful inspiration for novel approaches in architecture. In this chapter, a variety of biological systems are introduced: *Bacillus subtilis*, the green alga *Euglena gracilis*, diatoms and red blood cells. Subsequently results of bionanotechnological research performed (by physicists) on these systems are presented. In the next step, the systems and the results are discussed with an architect, resulting in a multitude of ideas, possible approaches, experiments and projects. Such interdisciplinary access corroborates the power of collaboration across established fields in modern science and technology.

1. Introduction

Biological systems with functional units in the micro- and nanometer regime continuously inspire novel micro- and nanotechnological applications.[1] Synergies between biology and mechanical engineering are manifold[2] and were the motivation to investigate synergies between bionanotechnology and architecture. Effective collaboration requires interdisciplinarity. However, with the huge knowledge in different fields, nowadays it is impossible for a single person to know and understand more than just a fraction. Nevertheless, the awareness and understanding of different approaches and concepts is a paramount prerequisite of interdisciplinary work.

A common language of bionanotechnologists and architects, in which descriptions at different level of detail are more compatible, is attempted here – the chapter is intended to be readable by both occupational groups.

General principles that can be applied by architects comprise integration instead of additive construction, optimization of the whole instead of maximization of a single component feature, multi-functionality instead of monofunctionality, and energy efficiency and development via trial-and-error processes. Systematic technology transfer from bionanotechnology to architecture thereby becomes generally accessible (Fig. 1).

Terminology. As in many other fields, for example information technology, the interpretation of the term „architecture“ was extended from the initial building construction related to the interpretation of a general system and construction principle, adaptable to any technical discipline.

In this way „nanoarchitecture“ can be interpreted as the design of new nanotechological materials and surfaces, by the controlled assembly of nano-scale „building“ blocks.

On the other hand nanotechnology increasingly finds its way into our everyday lives, so into the classic architecture and building construction as well. In order to avoid confusion, we will refrain from using the term nanoarchitecture for the application of nanotechnology in architecture.

Aims. The encounter of four selected projects in nanotechnology with current architectural developments will widen the interpretation and understanding of both disciplines and identify future research fields.

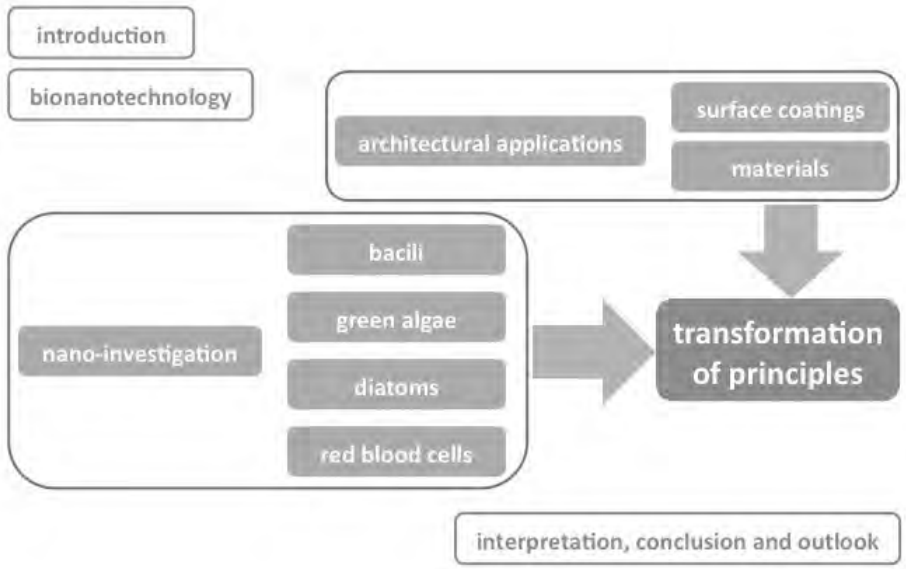

Fig. 1 Conceptual diagram of this bookchapter.

1.I. Current application fields of nanotechnology in architecture

Literature research was carried out for nanotechnological applications in architecture, to give an overview of the present state of the art. As proposed by Gruber P. in "Biomimetics in Architecture" in 2008[3] architecture is interpreted as multiscale discipline, from nanoscale to regional and urban planning. In general nanotechnology delivers functional optimisation of specific characteristics of building and construction materials. Comprehensive collections of nanotechnological applications in architecture are given by S. Leydecker[4] and the association of German engineers VDI[5]. Nanotechnology and a biomimetic approach have already delivered new products for architecture and building industry.

By means of further development in chemistry, physics and material science innovation in the field of nanotechnology in architecture are made possible. In the following, present research aims are presented:

- Production of new nano-objects and nano-systems, for example spheres, crystals, plates, fibres, layers and branching structures.
- Design, control and regulation of new or optimised material characteristics, for example chemical reactivity, hardness, flow properties, colour and transparency, protective function, electrical conductivity and magnetism.
- Improvement of materials and production processes, also concerning environmental and economic issues.
- Solution of complex problems in an intelligent and economic way.
- Improvement of interior climate, comfort of living and safety in buildings.
- Improvement of durability of buildings, amongst others elements the facades, windows, doors, roofs etc.
- Reduction of energy consumption.

• Improvement of energy efficiency and durability of cement-bound materials.

• Improvement of durability of tarmac, a widely used pavement material.

Current application fields are not restricted to surfaces, but this field is vast in contrast to the fewer developments on the side of actual materials. The difference between surface structure and material characteristics will be the main criterion used to order the field. This might be in opposition to materials research, but is a useful differentiation used in architecture and building.

Surface coatings

Surface coatings of construction materials and products are very common. They are used in the inside and outside of buildings to change the characteristics of the elements surface in providing a new functionality that cannot be achieved with the material as such. The production of these coatings is usually by bulk, and the application techniques range from conventional painting to spraying and other methods. The effectiveness of the coatings is due to the designed surface geometry and catalytic processes.

Functions that can be achieved are described in the following.

• Self cleaning and easy-to-clean function

Self cleaning of surfaces is based on the well known Lotus-effect[6], by the creation of a super hydrophobic surface. The company STO is the market leader in facade colour and plaster (http://www.sto.de). Similar principles are used for protection from graffiti on wall painting.

The contrary effect, hydrophilic surfaces, is used for anti-fog function. They create an invisible thin film of water instead of visible droplets.

Photocatalytic effects work in the combination of air humidity, UV radiation, oxygen and the nanoscale catalyst TiO_2. The surfaces are cleaned with water from decomposed dirt particles.

In contrast to the Lotus-effect surfaces, easy-to-clean surfaces are smooth, hydrophobic and oleophobic. Water rolls off due to the hydrophobic surface characteristics.

• UV protection

Inorganic UV protection is a novelty in building industry. The three chemical compounds, TiO_2, ZnO and CeO are used to absorb UV radiation and protect material from ageing. Particle sizes below 15nm ensure transparency. Many research groups and companies are working in this field.

• Switchable transparency and darkening

A new development in electrochromic glasses, whose transparency and darkening is switched with electric voltage, allows the use of adaptive darkening without continuous use of electrical energy. A memory effect in the functional nano layer is responsible for the effect. Different grades of transmission are possible. Photochromic glass changes colour according to environmental light conditions. Large glass producers meanwhile offer electrochromic products for architectural application under the title “smart glass” (for example Saint Gobain, Sage Electrochromics).[7] The basic technology was developed by the Lawrence Berkeley National Laboratory in the 1990ies.[8]

• Anti reflectivity

Nano-scale surface structures that are smaller than the wavelength of visible light, for example SiO_2 spheres, deliver efficient anti-reflective solutions. The use of biomimetic structures is also possible: In 2006 the US company Reflexite developed an antireflective knobbed surface that yields in the wavelength band between 400 and 700 nanometers a reflectivity of less than one percent.[9] The inspiration for this product came from work on moth eyes from Vukusic and Sambles that was published in Nature.[10]

• **Anti fingerprint**

Anti fingerprint coatings change the refraction of metal or glass surfaces in a way that fingerprints are no longer visible, delivering a clean appearance.

• **Fire protection**

SiO_2 based gels are used in a millimetre thin layer as functional filling in glass, and deliver excellent fire protection. Nanoparticles in coatings are applied to glass, wood, metal, plastics or concrete. In case of fire they produce a ceramic protective layer. Other nano-additives are used in organic fibre materials reducing inflammability.

• **Anti bacterial effect**

Silver nanoparticles deliver photocatalytic and anti bacterial effects, and are used for interior materials, for example floors, textiles, sanitary surfaces etc. In this way the use of disinfectants can significantly be reduced.

• **Scratch proof and abrasion proof**

Self healing or glasslike scratch proof and abrasion proof surface coatings can be used for different materials, for example wood, metal and ceramics.

• **Air cleaning**

Catalytic processes are used for air cleaning. The degradation of organic substances delivers uncritical components.

• **Microcapsules for fragrances**

Microcapsules set fragrances free when they break during pressure or friction. They are used in interior design, and are activated by the user.

Materials

Nanomaterials are either thin layers or composite materials, which are nano-structured. They are used for:

• **Insulation: Vacuum panels and Aerogels**

Vacuum panels deliver better thermal insulation values than conventional materials. The panels consist of a metal or plastic foil, enclosing the evacuated layer of foam, powder or fibrous material.

Aerogels, one of the few really nano-structured materials, is used in form of a granulate material for insulation fillings in glass or polycarbonate panels. Aerogel is an ultra light nanostructured foam with exceptional thermal and acoustic insulation properties.[11]

• **Temperature control: Phase change materials**

Phase change materials deliver latent energy storage by melting and freezing. Paraffin in nanoscale plastic spheres absorbs energy without temperature increase. By absorbing peak temperatures, interior spaces stay cool for a longer period of time. The process works the other way around as well.

• **High performance lightweight concrete**

Nanoparticles improve the bond in the so-called “Nano-concrete”, thus improving material properties as well.

• **Optimisation of characteristics of cement bound materials in general**

• **Materials for energy harvesting**

High temperature fuel cells for electricity and heat production with gas can be more efficient with the use of nanostructured membranes and catalysts.

• **Solar cells**

Nanotechnology is used to create dye-sensitized solar cells, a promising development in photovoltaic applications.

• **LEDS**

Light emitting diodes are increasingly used as energy efficient lighting technology.

1.II. Atomic Force Microscopy and Spectroscopy

Bioimaging with the atomic force microscope (AFM) has become an ambitious field of research in the last two decades. It has increasingly been used to image microbiological samples at ultrahigh resolution. There are several advantages of using the AFM for biological investigations. The AFM is not only an instrument for imaging sample surfaces, there is also the possibility to measure various physical properties such as mechanical properties, surface charges, molecular interactions, magnetic properties, friction forces and surface hydrophobicity.[12] The AFM techniques can also be used to manipulate living samples and surfaces. The main advantage of using the AFM for biological specimens is the ability to analyze non-conducting surfaces without additional preparation such as metalizing with gold which would have an influence on the biological properties of the samples. The second advantage is the non-destructive method of imaging the biological samples by using the AFM in the so-called dynamic mode.

Yet another AFM imaging mode is called phase imaging.[13] By mapping the phase of the cantilever oscillation during the dynamic mode scan (the cantilever is one of the main parts of the AFM with a sharp tip on its end used to scan the sample surface), phase imaging goes beyond simple topographical mapping to detect variations in composition, adhesion, friction, viscoelasticity, and possibly other properties. Applications include identification of contaminants, mapping of different components in composite materials, and differentiating regions of high and low surface adhesion or hardness.

One interesting topic for medicine, biology, industry and ecology is nanoscopic investigation of cell surfaces. Cell walls have properties that can provide information on the interaction of pathogens with tissues and the accumulation on implants[14] in medicine, show advantages in biotechnology, such as cell immobilization in reactors and water safety treatment, e.g. *Bacillus subtilis* for managing drinking water quality safety.

The reason why cell surfaces play such an important role is their ability to interact with the environment and to protect the cytoplasm from outer dangers. Cell surfaces act as molecular sieves and control interfacial interactions, such as cell adhesion and aggregation. In order to understand these functions, the structural and physical properties of the cell surface have to be investigated. There are several methods[15,16] for investigating these properties: X-ray photoelectron spectroscopy, infrared spectroscopy, electrophoretic mobility measurements, electron microscopy, and many other chemical and technical methods, which all have the disadvantage of destroying useful information during the preparation process, because of the required extensive cell preparation procedures. By using the AFM it is possible to investigate the cell surface properties under physiological conditions and at ultrahigh resolution. One of the current investigation topics is the change of the cell surface structure under native conditions and the visualisation of effects induced by external agents. AFM investigations of the influence of chemicals, enzymes, solvents, ions and antibiotics may reveal significant changes of the properties of microbiological cells that cannot be detected with other methods.[17] This advantage provides that cell growth, budding processes (i.e. forming a new organism by the protrusion of another organism) and the change in cell surface morphology resulting from treatment with external agents

can be investigated *in situ*. Molecular interactions play a big role in understanding medical and biological processes and are essential for the study of human health. By using an AFM equipped with a closed fluid cell, the living conditions and nutrients can be changed during the measurement in order to observe changes of cell structures and their morphology in different environments. The sample fixation, using a fluid cell, is challenging, but in some cases, especially for vegetative samples, it is indispensable to use a fluid cell.

Another useful AFM application is the cell-probe technique, where the cells are directly attached to the AFM probe. The cell-probe method can be used for recording force vs. distance curves. Another field of usage of the AFM is the nanomedical investigation. AFM cantilever tips functionalized with biomolecules are used to investigate forces between ligands and receptors. For obtaining representative results of the chemical properties and intermolecular forces of a biological sample surface, it is important to know the chemical characteristics of the cantilever. There have been many probes developed with a well defined tip-chemistry. These probes are usually functionalized with self-assembled monolayers (SAMs), which are very sensitive to chemicals and have a high spatial resolution.[18] For the investigation of cells with the AFM it is necessary to work in parallel with an optical microscope to control the cantilever tip approach to distinct cellular features.[19] The cell behaviour influenced by growth, gene expression and cell cycle progression is closely related to changes in their physical properties.[20] The measurement of the changes of elasticity will provide a better understanding of these processes.

The elasticity of the cell can be measured by using indentation techniques.[21] By pressing the cantilever with a pre-defined force into the sample surface, force vs. distance curves are obtained to determine the compressibility of the cell wall. The AFM tip is approached towards and retraced from the surface, while the force between the tip and the surface of the sample is recorded. The force vs. distance curves are a function of the z-value and the deflection signal of the cantilever.[22] The comparison of force vs. distance curves can give information about elasticity differences in various samples.

Cross et al. report in 2007 in Nature Nanotechnology a change in stiffness in cancer cells as compared to benign cells[23]: Samples of lung, breast and pancreas cancer were studied with atomic force microscopy. It was found that the stiffness of metastatic cancer cells is more than 70 % smaller with a standard deviation over five times narrower than the stiffness of benign cells that line the body cavity.

Dulinska and co-workers investigated erythrocytes from patients with haemolytic anemias and patients with anisocytosis and found statistically relevant differences in stiffness: the Young's modulus of pathological erythrocytes was higher than in normal cells.[24] Observed differences indicate possible changes in the organization of cell cytoskeleton associated with various diseases.

Atomic force microscopy and spectroscopy studies on two systems, *Bacillus subtilis* and red blood cells, will be presented below. The results of these studies, and two more biological systems of interest, *Euglena gracilis* and diatoms, are further on discussed with an architect.

1.III. Bacilli

Bacillus subtilis (lat. bacillum/bacillus, stick; subtilis, simple) is a rod-shaped, gram-positive bacterium (gram staining is a method to differentiate bacterial species) with flagellae providing the mobility and the ability to sporulate (Fig. 2, sporulation is a form of adaptation to starvation).

Like every bacterium of the species Bacillus, *B. subtilis* grows in aerobe conditions and produces endospores as a result of sporulation. The endospores allow the organism to resist extreme environmental conditions concerning e.g. pH, temperature and nutrient shortage.[25] *B. subtilis* is not harmful to human health and its robust spores may serve as safe model organisms for pathogenic microorganisms in drinking water (e.g. in testing the efficiency of water treatment methods).

Morphogenesis. Sporulation is a mechanism of bacteria to adapt to starvation. In contrast to most adaptive responses in bacteria, sporulation takes many hours and includes major changes in cellular morphology as well as in biochemistry and physiology. Morphogenesis relies on the cooperation of two sister cells, which both are starting with the same genome. The first cell is packaged into a tough resistant coat, while the other cell contributes most of its resources to this process and then lyses (i.e. the cell dies after destruction of the cell membrane with the aid of a protein called Lysine). Morphogenesis is also an example for the differentiation of certain cells and for elaborated feedback mechanism between these two specific cells. The genetic interactions can be explained by the action of transcription factors. Sporulation is among the best understood of developmental systems and helps answering basic questions of biology at the molecular level.

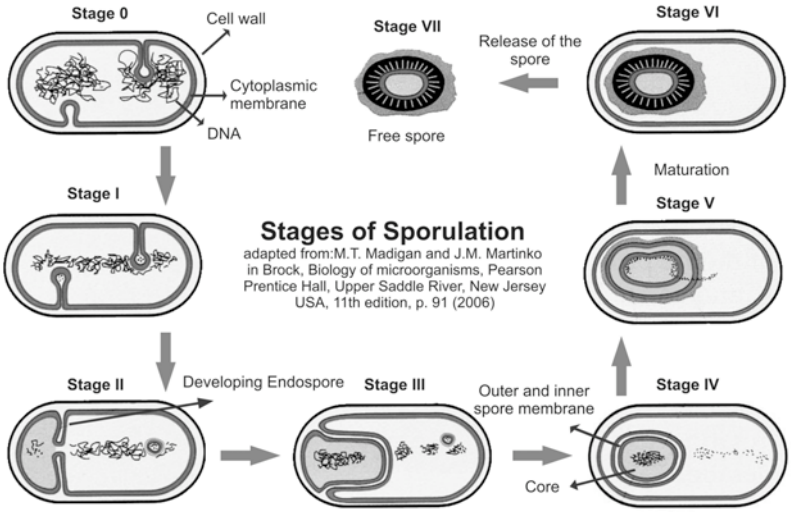

Fig. 2 Stages of sporulation in Bacilli.

By using the AFM phase imaging mode several cell properties can be measured. As mentioned above it is possible to investigate material properties such as adhesion and elasticity by recording the phase shift as a function of the driving signal. Although this imaging method is not very easy to perform on living cells, this imaging method is evolving rapidly.[26] Forces such as lateral and shear forces are reduced by using the dynamic mode, without damaging the cells. By using phase imaging the obtained image can be explained as a map of viscoelastic variations on the sample surface, and provide insight to the cells. A small positive phase shift indicates stiffer, a small negative phase shift softer regions, and might be displayed by brighter and darker regions within the recorded image, depending on the contrast settings of the AFM software.[27] One influence of the phase shift signal is the surface stiffness; the second is the result of the viscoelasticity.

UV-sensitive and UV-resistant spores. The resistance to UVC and UVB radiation depends on the method inducing the sporulation process and therefore which type of spore is formed. *Bacillus subtilis* spores have been successfully established for the validation of water treatment processes like filtration techniques and disinfection processes most importantly for the biodosimetry of UV disinfection systems.[28]

1.IV. Green algae

The algal flagellate *Euglena* (Fig. 3) has for long been an outstanding subject of study, its species is one of the most completely studied.[29] These small yet complex unicellular organisms dispose over a plethora of bionanotechnological machinery in order to live, survive and procreate. Their long feature list includes amongst others a proteic crystal that acts as highly efficient light sensor, a flexible outer shell (the pellicle) that can actively change shape, a mobile thread (the emergent flagellum) enabling

them to move with high speed through the liquid, and chloroplasts converting sunlight photons into storable energy.

The ability to "feed" mainly on sunlight (although it must take up the vitamin B-12, which it cannot synthesize itself, from the surrounding) and to survive even with no light present at all by forcing itself to heterotrophic metabolism has raised some discussion whether this organism is more 'plant-like' or 'animal-like'. Photosynthesis (and its prerequisites, the chloroplast plastids within the cell) is a strong argument to classify it amongst plants, yet an *Euglena* cell has no cellulose cell wall (its protective hull, the pellicle, is inside the plasmalemma) and is a very active swimmer using its whip-like flagellum, an ability rather associated with animals. This lets guess the unusual cross-functionality regarding metabolism, organelles and lifecycle exhibited by *Euglena*.

Interesting subsystems of *Euglena gracilis* can be found on every scale[30], from its entire body pellicle down to the light capturing and transduction mechanism where even single atoms play a major role. Many aspects are still actively researched such as the mechanics of proteinaceous strips composing the pellicle, the biochemistry of rebuilding lost chloroplasts, the electrochemistry of aforementioned signal transduction from the stimulated light receptor, the biophysics of concerted microtubuli contraction and detraction for euglenoid movement (a second mode of movement described below) and many other processes sometimes also to be found in other living systems.

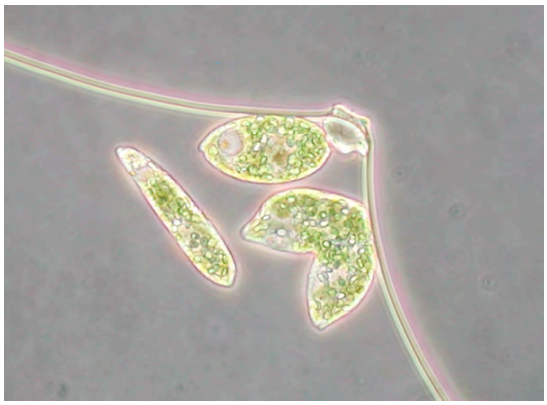

Fig. 3 *Euglena gracilis* cells under the optical microscope. The length of one cell is about 50 µm. The rightmost cell can be seen in the process of cell division. This takes about 2-4 hours after which two equal daughter cells can begin their new lifecycles. In that sense an *Euglena gracilis* cell never dies, but lives on in its offspring.[31]

Photoreceptor. The word "*Euglena*" is formed from the two Greek words "*eu*" and "*glene*" which mean "good" and "eyeball" respectively, because of the clearly visible (with optical microscopes) stigma (Fig. 4), also called the eyespot.[32] Originally it was thought that this "eyespot" was light-sensitive and used by the alga to direct itself towards the light. But we know today that its role is only to intermittently shade the photoreceptor (attached to a flagellum inside the reservoir of the cell) as the cell revolves around its long axis. In this sense the eyespot is only a sub-part of the algal optical system.

The ability to perceive light and adapt to changing light conditions is crucial to photosyntactic organisms, therefore detecting low light intensities becomes an adaptive advantage. A photosynthetic organism in dim light can obtain more metabolic energy if it is able to discriminate and move toward better illuminated areas.

The photoreceptor is connected to the flagellar rod and protected by a surrounding membrane. It is a highly efficient light detector and is shielded on one side by the stigma (the eyespot). The stigma consists of tiny carotenoid granules that absorb light in the sensitivity range of the photoreceptor. This

simple but complete visual system allows *Euglena* to orientate itself towards a light source.[33] The light-orientated movement of the cell, called phototaxis, is caused by the teamwork of the stigma and the photoreceptor. During its movement, the cell permanently rotates and the stigma comes between the light source and the photoreceptor. *Euglena* experiences a periodical dip in light intensity and changes its direction of movement until the detected light is no longer modulated by the stigma. Then the cell is moving towards the light source.

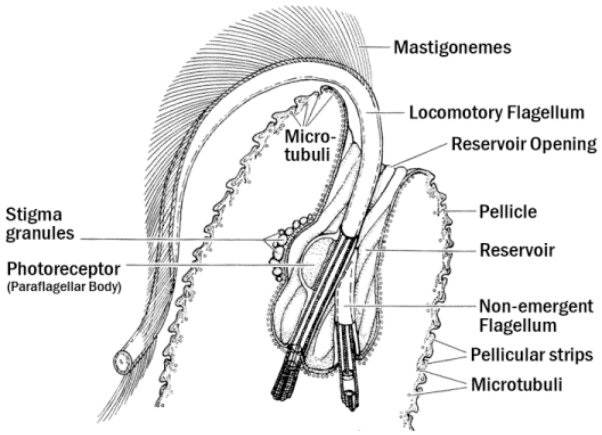

Fig. 4 Apical part of *Euglena viridis*. Image adapted from[34].

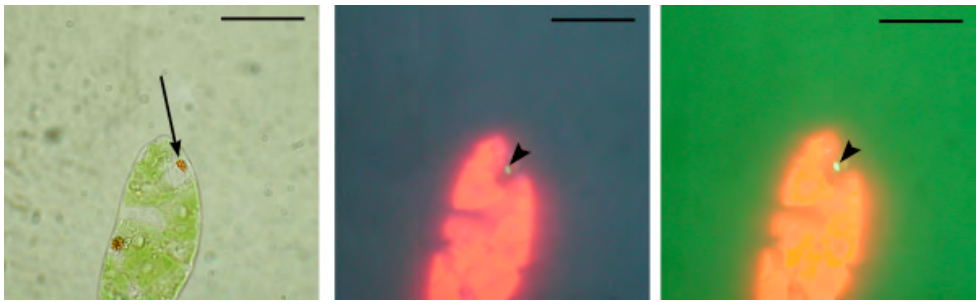

Fig. 5 Three images of the apical part of the same cell. The leftmost image shows the cell as seen in phase contrast, with no UV-light illumination. The image in the middle shows the cell during illumination with 365 nm light - upon absorption of photons of this wavelength the rhodopsin-like proteins present in the Euglena photoreceptor change into the excited state. The green emission of the photoreceptor is only faint. In the rightmost image, the cell is irradiated with photons of 436 nm wavelength. At this wavelength the light sensitive proteins fall back into the ground state, emitting bright green light and completing the photocycle. Arrowheads indicate the photoreceptor crystal in the images, the arrow indicates the stigma responsible for intermittently shading the alga when rotating during swimming. The scale bar in each of the images is 20 µm.

The photoreceptor is the exceptional light-sensing unit of the alga. It is a small proteic crystal and enables the alga to detect even very low light intensities (i.e. single photons). Although the photoreceptor is only 1µm in diameter, it reaches an absorption rate close to 100% of the incident light within its absorption band spectrum. The sensitivity of its photoreceptor is so high because it is made of a stack of many pigment containing membranes (around 100 layers).[35]

Embedded within the layered structure of the photoreceptors is its main ingredient, a rhodopsin-like protein. Rhodopsins are special proteins for intercepting light, universally used from archebacteria to humans, consisting of a proteic part, the opsin, organized in seven transmembrane helices, and a light-absorbing group, the retinal (i.e. the chromophore). The retinal is located inside a pocket of the opsin, approximately in its center. Several properties make the retinal-opsin complex an excellent light detection unit. It has an intense absorption band whose maximum can be shifted into the visible region of the spectrum, over the entire range from 380 nm to 640 nm. Second, light isomerizes the retinal inside the protein very efficiently and rapidly. The isomerization, i.e. the event initiating the vision reaction cascade, can be triggered almost exclusively by light. In the dark it occurs only about once in a thousand years!

The isomerization and possible conformational changes of the protein follow a photocycle and are therefore repeatable (Fig. 5). The photocycle leads through a series of conformational changes from the initial state to an excited state and back again. Usually also a number of intermediates can be identified. The photocycle of the chromophore in the photoreceptor of *Euglena* shows such a cycle including a ground and an excited state. As different conformational states possess different fluorescence characteristics, a photoreceptor whose chromophore proteins are mostly excited differs in emission characteristics from a photoreceptor containing chromophore protein mostly in the ground state.

The time it takes for the whole photocycle to complete is on the order of microseconds or less. The isomerization alone is one of the fastest processes ocurring in nature, completing in about 200 femtoseconds (i.e. $200*10^{-12}$ s).[36]

Pellicle. If the cell cannot use its flagellum for locomotion it can move by the so-called “euglenoid movement” (similar to that of a worm contracting the back and extending the front part) - sliding along solid material and being lubricated by its own muciferous lubricant excreted from pellicle pores. This kind of movement can be induced when only little space is given to the alga to move, e.g.between two flat glass slides. The pellicle of *Euglena* has evolved into a very elastic and refined structure that supports such a viscous change in shape during euglenoid movement.

The boundaries of the *Euglena* body are formed by the outer tripartite (three-layered) plasmalemma membrane surrounding the pellicle composed of interlocking and articulating flexible strips (Figs. 6 and 7). These ribbon-like strips are arranged in a left-handed spiral and interwoven with microtubuli.

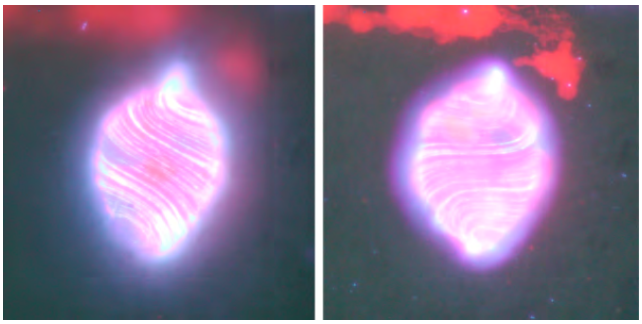

Fig. 6 Twice the same *Euglena* cell as seen with an optical microscope, using UV-light illumination. The focal plane in the left image is adjusted such that the part of the pellicle closer to the observer is rendered. The image one on the right shows the far side of the pellicle. The light-dark pattern follows the alignment of pellicle strips fusing partly at top and bottom.

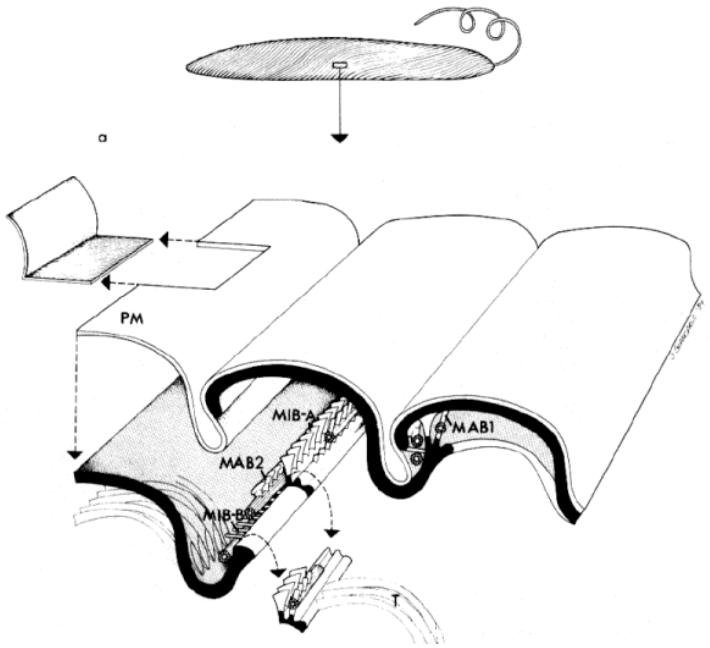

Fig. 7 On top of a swimming *Euglena*: The schematic drawing depicts a transverse section of its cell surface. Details of the articulating S-shaped strips of the membrane skeleton and the infrastructure associated with strip overlap. The position of the skeleton and the bridges are well suited to mediate the sliding of adjacent strips occurring during shape changes. The portion of the plasma membrane not subtended by the cytoskeleton may provide the fluid region, which accommodates sliding as well as a region for the insertion of new strips during surface replication. The traversing fiber is positioned to maintain the S-shaped configuration and it may contribute an elastic component to the sliding skeleton. MAB1 and MAB2, microtubule associated bridges; MIB-A and MIB-B, microtubule independent bridges; PM, plasma membrane; T, traversing fiber.[37]

The pellicle defines the basic shape of the cell. Its role is vital to the organism as it must function as protection from the environment, yet cannot be fully impermeable as it must permit e.g. exchange of information or matter with the exterior as in sensory pathways or uptake of the vitamin B12. Additionally, euglenoid movement requires the strips of the pellicle to be highly flexible and articulate against each other. The cells also show excellent pressure resistance up to 100 bar and beyond.

There is strong evidence that the microtubuli within the strips (aligned in parallel) together with motor proteins are responsible for the sliding of the strips against each other, meaning the pellicle changes its shape actively at the command of the cell! The fact that this protective shielding is self-assembling through means of specific binding sites inside the plasmalemma membrane and binding proteins adds to this exceptional part of *Euglena*.[38]

If the cell is disrupted the pellicle can be seen dissociated along the striations into flat strips of material which have a thickened edge and a thinner flange. Electron microscopy sections clearly show how these strips interlock and how they pass helically along the cell. These strips are intracellular structures lying immediately beneath the plasmalemma, a continuous tripartite membrane about 0.8 – 1 μm thick. The pellicle is thus not equivalent to a cell wall, since the latter is always laid down

outside the plasmalemma (like a cellulose wall of plant cells). The throughs between adjacent strips start as a whorl at the posterior end of the cell, bifurcate a few times before passing helically along the length of the cells and then meet again as they reach the canal opening. The strips of the pellicle curve over and continue into the canal, where they also fuse. Although variation occurs concerning thickness and shape the form of construction is the same in all euglenoids. The cross section of a pellicle surface can be seen in a schematic drawing in Fig. 7.

1.V. Diatoms

Diatoms are unicellular microalgae with a cell wall consisting of a siliceous skeleton enveloped by a thin organic case. 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[39,40] (Fig. 8).

Diatoms are found in both freshwater and marine environments, as well as in damp soils and on moist surfaces. They are either free floating (planktonic forms) or attached to a substrate (benthic forms) via biogenic adhesives, and some species may form chains of cells of varying lengths. Individual diatoms range in size from 2 μm up to several millimeters, although only a few species are larger than 200 μm. Diatoms as a group are very diverse, with 12 000 to 60 000 species reported.[41,42]

Diatoms can serve as model organisms for micro- and nanotribological investigations[43,44,45] and as templates for novel three-dimensional microelectromechanical systems (MEMS)[46,47]. In ambient conditions, these organisms produce nanostructured amorphous silica surfaces. Some diatom species have rigid parts that in relative motion act like rubber bands when elongated[48] and subsequently released, whereas other diatom species have evolved strong, self-healing underwater adhesives.[49] Diatoms are small, mostly easy to cultivate, highly reproductive, and, since many of them are transparent, are accessible using optical microscopy methods.

Already in 1999, Parkinson and Gordon[50] pointed out the potential role of diatoms in nanotechnology via designing and producing specific morphologies. In the same year, at the 15th North American Diatom Symposium, Gebeshuber and coauthors[51] introduced atomic force microscopy and spectroscopy to the diatom community as new techniques for *in vivo* investigations of diatoms. These scanning probe techniques not only allow for the imaging of diatom topology, but also for the determination of physical properties like stiffness and adhesion.[52,53,54,55,56,57] A representative example of the fruitful exchanges in the area of diatom nanotechnology can be found elsewhere.[58]

Hinges and interlocking devices in diatoms are very stable and can still be seen in fossil deposits millions of years old (Fig. 8).[59] In 2006, Gebeshuber and Crawford[60] presented scanning electron microscopy (SEM) images of extinct and recent diatom species with linking structures with the aim of correlating structure and function. Fig. 8 shows four connections of two *Solium exsculptum* sibling cells that lived 45 million years ago and are still in good condition.

Perhaps we might even soon be able to evolve the kind of nanostructures we want and replicate them in large numbers via the way diatoms naturally replicate – cell division: a compustat[61,62] could monitor diatom properties and selectively destroy cells that do not evolve in the desired direction. In this way, directed evolution would take place. This conveyor belt-type production could yield nanostructures for use in technological applications. The amorphous silicate material of the diatom cell wall is not very interesting for technological applications. However, recently Sandhage and co-workers introduced a method to replace the diatom silica with materials of technological relevance (such as silicon) while preserving the shape.[63,64,65,66] In this way, tailored diatom nanostructures are even more usable for devices.

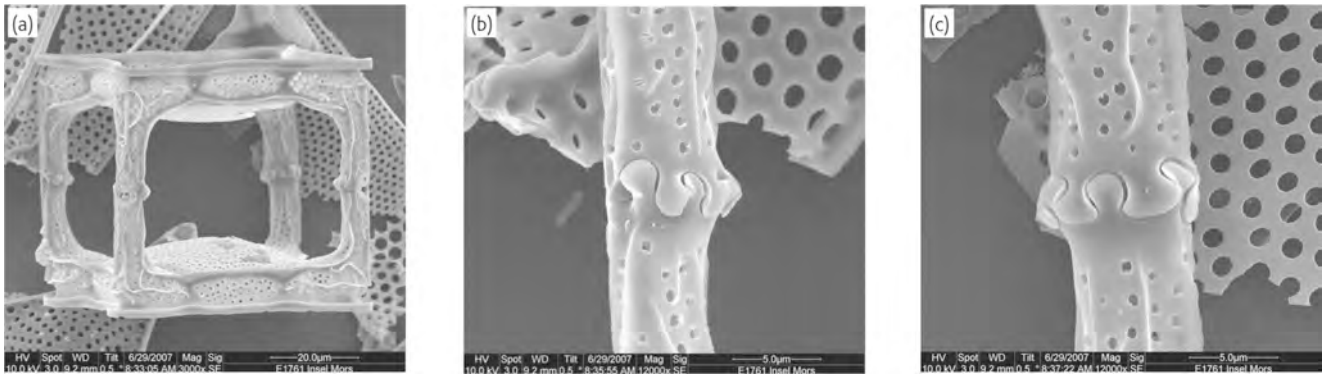

Fig. 8 a) b) c) SEM images of *Solium exsculptum*, an Eocene fossil (45 million years old) from a deposit at Mors, Denmark. **b)** and **c)** show the linking structures in more detail. Scale bars: 20 µm, 5 µm, and 5 µm, respectively. The sample is from the Hustedt Collection in Bremerhaven, Germany, # E1761. (Reproduced with permission. © F. Hinz and R.M. Crawford.)

1.VI. Red Blood Cells

Blood consists of blood plasma and different types of cells, the red blood cells (erythrocytes), the white blood cells (leukocytes) and the platelets (thrombocytes). The erythrocytes give the blood its red colour and are responsible for the oxygen transportation within the human body.

Red blood cells. Red blood cells carry oxygen to the periphery of the body and CO_2 from there back to the lung, exchange the gases and start the circle again. This is possible with the help of haemoglobin. There are about 4.5 - 5 million red blood cells per microliter blood.

Erythrocytes are about 7.5 µm in diameter and 2 µm in thickness. The cells are shaped biconcavely have a surface area of about 135 µm² and a volume of about 90 fl.

The erythrocytes shape indicates the hydration status of the body. Therefore certain diseases can be diagnosed by the investigation of the shape of the red blood cells and their surface properties. For example, hypertone dehydration leads to shrunken and wrinkled erythrocytes whereas hypotone dehydratation provokes balloon shaped red blood cells.

Erythropoietin. Erythropoietin (EPO) is a hormone that is produced by the kidney. It stimulates the bone marrow to produce red blood cells. Synthetic EPO is clinically used for treating renally caused anaemia and kidney diseases. In serious sports recombinant erythropoietin is used for doping. Recombinant erythropoietin is a glycoprotein that is generally expressed in Chinese hamster ovary cells that were transfected with DNA encoding for human erythropoietin. Applying recombinant EPO enhances the number of erythrocytes by about 5-20 %. This leads to increased oxygen transfer and better performance of the doped athletes. Synthetic EPO is difficult to detect, because of its natural occurrence and because it is metabolised within 6-12 hours.

A medical device based on a method similar to AFM stiffness evaluation that is fast and reliably detects doping with EPO directly on site would find wide applications in serious sports.

2. Materials and Methods

2.I. Bacilli

By inducing adverse environmental conditions to living *B. subtilis* cells the sporulation procedure is successfully initiated. Two methods of spores' production resulting in different types of spores are

included in the investigation. UV-sensitive and UV-resistant spores are prepared by standard methods and kindly supplied by the Institute for Hygiene of the Vienna Medical University.[67]

Preparation of spores in aqueous solution. The *B. subtilis* spore solution is centrifuged in order to remove unintentional artefacts. About 1 ml of this solution is dropped on poly-L-lysine coated and uncoated glass slides.

After fifteen minutes drying in air, some of the samples are washed with PBS (phosphate buffered solution) in order to reduce the spore density on the substrate. Depending on the inclined position of the slides during the washing and the amount of PBS used more or less *B. subtilis* cells remain attached to the slide. Then the sample slides are dried in air for about forty minutes before the atomic force microscope measurements are started.

Preparation of vegetative *B. subtilis* cells. Due to the limited lifetime of the vegetative *B. subtilis* cells and their ability to move by using their flagella the immobilization is an important aspect. The use of adhesively coated substrates turned out to be sufficient for mechanical fixing for AFM imaging. The preparation is the same as for the *B. subtilis* spores in aqueous solution described above, but in this case only substrates coated with adhesive poly-L-lysine for proper immobilization and PBS buffer solution for diluting instead of distilled water are used. The distilled water would initiate the bacteria membrane to burst because of the osmotic pressure.

The vegetative *B. subtilis* are usually dissolved in a nutrient solution. Nutrients can cause artifacts on the substrate surface during imaging.

To prevent artifacts on the glass-slide, a proper method is to smear off the excess solution with another slide. Due to the absence of water after drying the sample one has to consider that the bacteria will possibly start the morphogenesis, which can be intended in some cases e.g. for real-time imaging of changes in the bacterial membrane. To initiate the morphogenesis, the drying must occur not too fast because a little amount of water is required for the conversion from the living bacteria to the spore. Otherwise the majority of the bacteria would die before any morphological changes can happen.

Atomic force microscopy imaging. Dynamic mode AFM was used to investigate the *B. subtilis* samples. In dynamic mode there is only intermediate contact between the tip of the cantilever and the sample surface because the cantilever is oscillating at or close to its resonance frequency. This technique is used to avoid damaging the sample by scratching over it. Amplitude, phase and frequency information is obtained by tip-sample interaction forces. These modifications provide information about the sample's characteristics. In contrast to contact mode, in dynamic mode the cantilever oscillation amplitude is kept constant. Therefore the amplitude is permanently measured and a feedback loop adjusts the value of the cantilever z-value due to the distance between the tip and the sample surface which is defined by the set-point amplitude. Through this process the topography of the sample surface is obtained.

Different tip driving frequencies were used for imaging the spores. The best images were obtained using cantilevers with a resonance frequency of 70 kHz and a spring constant of 1.8 nN/nm (Olympus OMCL-AC240TS). The prepared samples were analyzed at different positions with an investigation area of 20x20 μm^2. The parts of interest were then magnified.

Measurement of indentation depth. Force vs. distance curves are used to determine the indentation depth of the cantilever tip into a sample due to a preset force trigger point. The penetration depth is a parameter for the stiffness of the cells. It is calculated by the position of the cantilever when the predefined trigger point is reached, minus the position of the cantilever when it is in first contact with the sample surface. On each spore a path is created that consists of 15 predefined points. On these locations force vs. distance curves are recorded. The preset trigger forces are 3 nN and 12 nN, respectively, and the curves are acquired with 1 Hz, 2 Hz and 4 Hz (Hz refers to the number of force

vs. distance curves recorded per second, indicating different pulling speeds). Altogether, 2760 indentation data points on UV-sensitive and UV-resistant spores are obtained.

2.II. Red Blood Cells

There are several reasons for using the atomic force microscope in studying blood cells; the most important is that the AFM is a general purpose instrument for analyzing surfaces at ultrahigh resolution, in ambient, fluid or vacuum conditions. Compared to other analytic instruments the AFM and especially the ambient AFM has a variety of advantages. The main advantage is the ability to analyze non-conducting samples without additional preparation such as metalizing with gold or similar techniques.

For the experiments the stiffness of blood samples of renal insufficient patients (i.e. patients with kidney problems), who are medicated with synthetic EPO and blood samples of a control group (healthy individuals) are compared. The maximum age of donors was 50 a.

After the standard procedure of preparation of the blood samples[68,69,70,71] the cells are imaged with the AFM using dynamic mode. Subsequently AFM force vs. distance curves are recorded and evaluated for differences in penetration depth.

The images are recorded in dynamic mode to prevent damaging the sample by scratching over it, with cantilevers with 70 kHz resonance frequency in air and a spring constant of 1.8 nN/nm (Olympus OMCL-AC240TS). The scan frequency is 0.43 Hz (i.e. a little bit less than two lines per second), the image size is originally 20x20 μm^2, regions of interest are subsequently scanned with smaller scan size.

For the question if there is a difference in the stiffness and plastic deformability of the control group and EPO medicated patients, the most interesting parameter is the penetration depth. The penetration depth is the parameter for the deformability of the cells. It is evaluated by the position of the maximal movement of the piezo sensor in z-direction, which is the coordinate when the sensor reaches the trigger point of 3 μN, minus the position of the sensor when the tip is in first contact of the surface of the red blood cell.

2.III. Bio-Inspired Nanomaterials and Nanotechnology in Architecture

For the development of further concepts, a mutual biomimetic approach is used. Usually – as described methodologically - biomimetic translation occurs from either end of the process: the natural phenomenon or the technical problem. The connotations “bottom-up” and “top-down” biomimetics (as introduced by Speck and co-workers[72]) are not used since they might imply hierarchical relation between biology and technology. According to Gebeshuber and Drack (2008) the methods of biomimetics by analogy and biomimetics by induction are used simultaneously, in imposing current issues and discussions in a specific field (architecture) onto a set of bionanotechnological investigations (bacilli, green algae, diatoms and red blood cells, Fig. 1).

3. Results and Discussion

3.I. Bacilli

This section presents the first high resolution AFM results on various stages of the sporulation process in *B. subtilis*. The different stages of the sporulation process are clearly discernible (Fig. 9). Starting from the vegetative *B. subtilis* (Fig 9a) the bacillus enters stage I (asymmetric cell division, Fig. 9b) and the developing endospore is appearing (stage II, Fig. 9c). The development of the prespore (Fig. 9d, the cell is in stage III, IV or V) leads towards the release of the mature spore by lysis of the mother cell (stage VI, Fig. 9e). Stages III, IV and V are not discriminable with surface methods such as AFM. At the final stage of the sporulation process, the spores appear (stage VII, Fig. 9f).

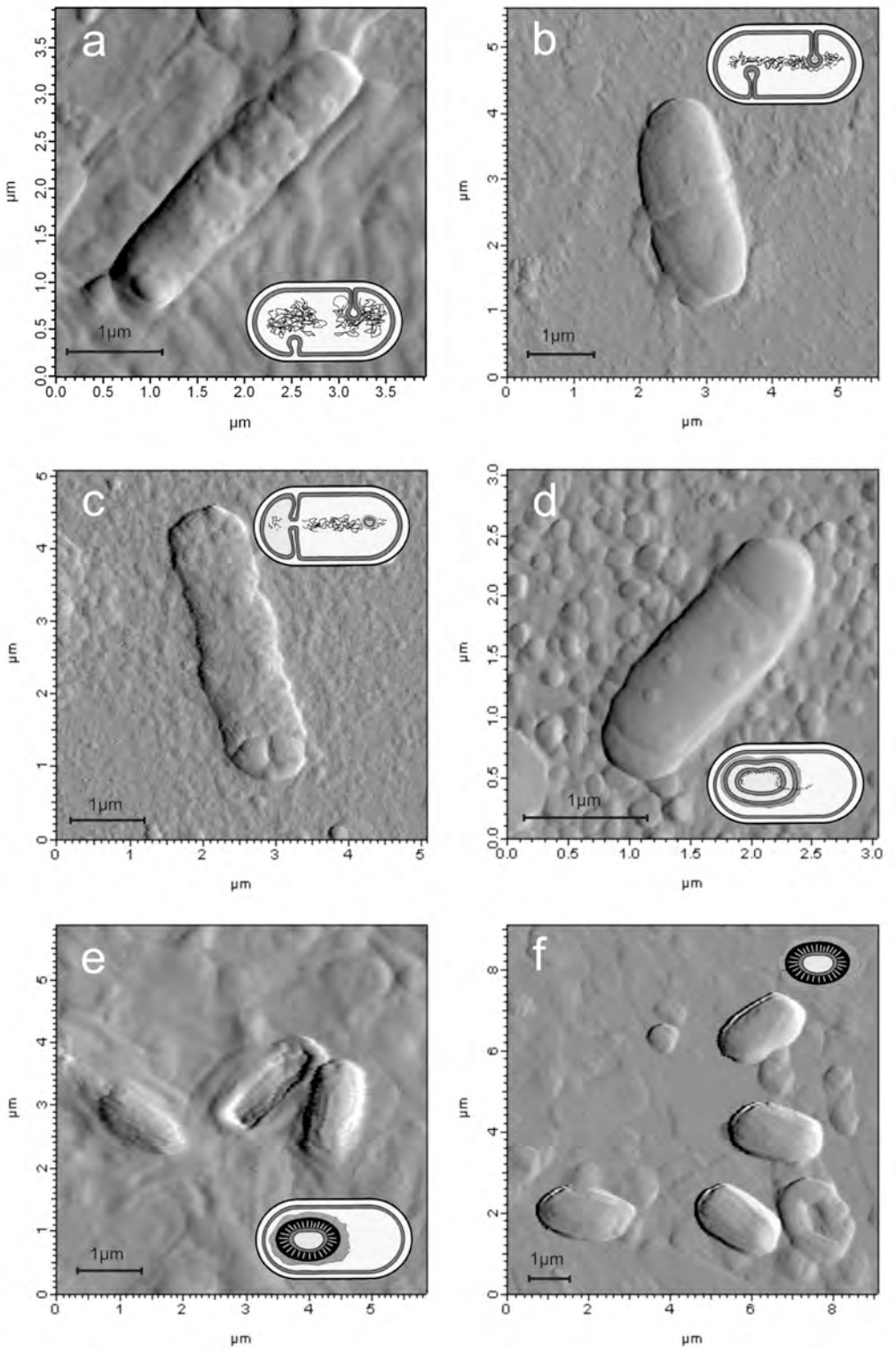

Fig. 9 Stages of the sporulation of *B. subtilis* imaged with atomic force microscopy. Dynamic mode, imaging parameter amplitude. The different stages are clearly visible (see text).

Furthermore, phase images of UV-sensitive and UV-resistant spores reveal distinct differences in the structure compound which refers to different elasticity of the spore coats (Fig. 10). The darker regions (i.e. smaller phase signal) in Fig. 10 indicate softer spore surface areas and the brighter regions indicate stiffer spore surface areas. The structure of the UV-sensitive spore is divided into small softer

regions surrounded by a stiffer grid (Fig. 10). The UV-resistant spore (Fig. 10, right trace) has large regions that are stiffer than the rest of the spore. These differences in stiffness are representative for UV-resistant and UV-sensitive spores, and are found in all recorded samples.
2760 indentation data points on UV-sensitive and UV-resistant spores are recorded. The UV-resistant spores are overall stiffer than the UV-sensitive spores, which correlates with the obtained phase images. It is found that the indentation depth in UV-sensitive and UV-resistant spores shows distinct differences when the indentation force exceeds a few nanonewtons: Considering the mean indentation depth of a preset force of 3 nN there are no significant differences in the penetration depth and therefore no difference in the stiffness of the spore. Using a preset force of 12 nN shows distinct differences in the indention depth of the UV-sensitive and UV-resistant spores (Fig. 11).

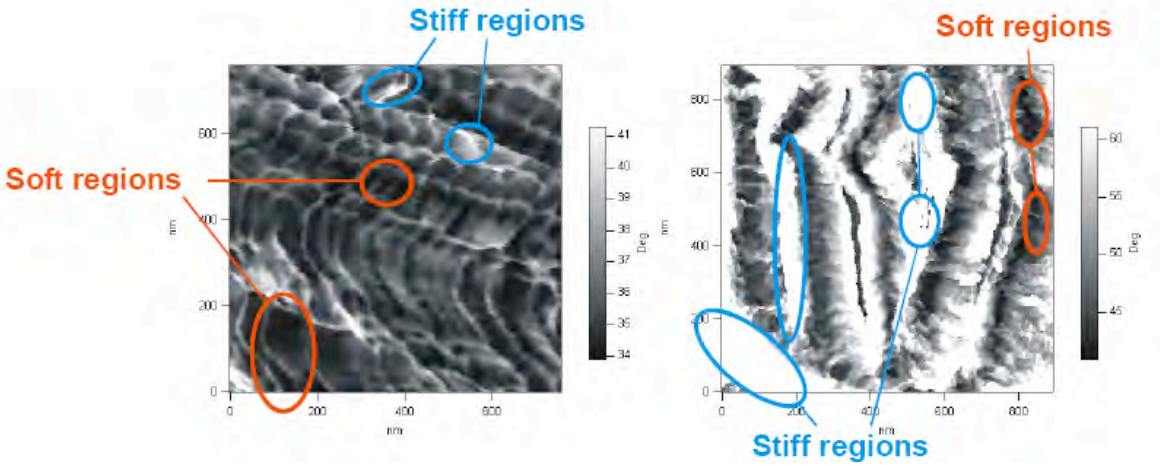

Fig 10 left: Typical phase trace of a **UV-sensitive endospore**: there are only few stiff regions separating small softer areas. Scan size 667x667 nm^2. **right:** Typical phase trace of a **UV-resistant endospore**: large stiff areas with small soft regions in between. Scan size 892x892 nm^2.

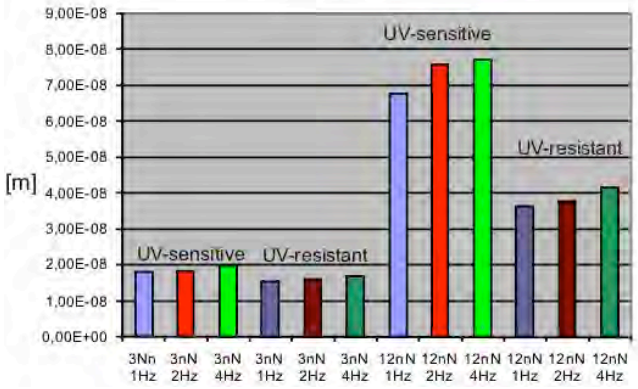

Fig. 11 Indentation depth in UV-sensitive and UV-resistant *B. subtilis* spores. Differences are very distinct for an indentation force of 12 nN (right trace) as compared to an indentation force of 3 nN (left trace). UV-sensitive spores have smaller stiffness.

Biomimetic inspiration by bacilli for architecture – results of the discussion

Transformation of principles

The most interesting characteristics of *Bacillus subtilis* are its sporulation ability, the adaptive shape and spore UV sensitivity in combination with the skin structure of the spores.

Spores

The spores of the bacilli must sense the environment and check if the environmental conditions have improved. How this is achieved is not known yet.

Sporulation as escape

The bacillus stops reproducing if there is a shortage of nutrients and retracts into spore state. If viewed as a retraction phase, the spore phase is very interesting for architecture: if the outside conditions are adverse, retraction provides protection for the inside. In terms of architecture, the analogy is shelter, providing protection from attack or other hostile influence. Extreme environments like polar stations or outer space require permanent extraordinary protection measures. Temporary measures of retraction, for example the retreat of inhabitants to warmer core zones of the house in winter, are used as strategies for energy efficiency in traditional architectures. The zoning of space according to temperature is again state of the art in sustainable design, but the architecture itself cannot yet be retracted. Currently rooms that are not needed are only abandoned, but remain existent. A more dynamic approach to architectural material could provide spore-like states as living environment as well and might prove to be more energy efficient. Adaptive shapes that react to daily or seasonal changes would be the solution.

On another scale, migration according to climate already exists in many also modern human cultures. The so-called snowbirds, retired people in the US who stay during the summer in the north of the US and move to warmer states in the winter, and the fast increasing tourism industry are recent examples. Both phenomena use plenty of resources and energy.

Principle of mother and daughter

The development of the one inside the other is also interesting for propagation in adverse environments. The interior environment is separated from the outside, controlled and provides the milieu that is needed for replication. Possible scenarios are toxic ambient air, too little oxygen, dangerous radiation etc. For space applications, an analogue environmental problem exists, with the hostile space environment. For space missions, the transport weight and volume are crucial parameters. Everything has to be sent in a space-saving way, so often folded structures are used. But on the other hand for space habitats sealing is always challenging, e.g. if a cap has to be added to a foldable structure. The development of the one inside the other would mean to develop a larger space habitat inside the milieu of the already sealed space of the transport capsule.

UV sensitivity

The membranes of *B. subtilis* UV-sensitive and UV-resistant spores differ structurally concerning the dispersal and pattern of hard and soft areas. The differentiation may have a functional relation with UV sensitivity, but it is still unknown. Apart from showing increased stiffness, the pattern of the UV resistant spore membranes seems to be a highly ordered system. The change in stiffness areas of the cell membrane in a pattern hints to a more dynamic kind of adaptability as well – maybe shape change is possible here as well. More investigation on the structure/function relation would clarify the case.

UV-sensitivity of *B. subtilits* is exploited as a biosensor. Sense, if and how the environment changes and react to it. UV absorbtion is important in building industry. The development of better and cheaper ways of blocking UV radiation would be economically very interesting.

3.II. Red Blood Cells

After imaging the erythrocytes, force spectroscopy with trigger forces of three micronewtons is performed on each single cell along preset paths in ambient air. About 200 force vs. distance curves are recorded per sample, 26 samples are investigated.

The penetration depth does not reveal statistically relevant differences in healthy and EPO blood samples. However, the penetration depth of samples 10 and 11 is four times higher than the penetration depth of the other samples (see Fig. 12).

There are also abnormalities of the surface of the blood cells of the donor of samples 10 and 11. The erythrocytes do not have the typical donut shaped form. These blood cells are oblate and very flat. These two blood donations are from the same donor. The measurements are repeated in order to ensure that no destruction of the sample during transportation or preparation took place. The previous result is confirmed, the cells are oblate and flat and the penetration depth of the cantilever is four times higher than in the other samples, indicating softer cells. After more detailed medical investigation a rare case of diabetes is diagnosed in the donor of samples 10 and 11.

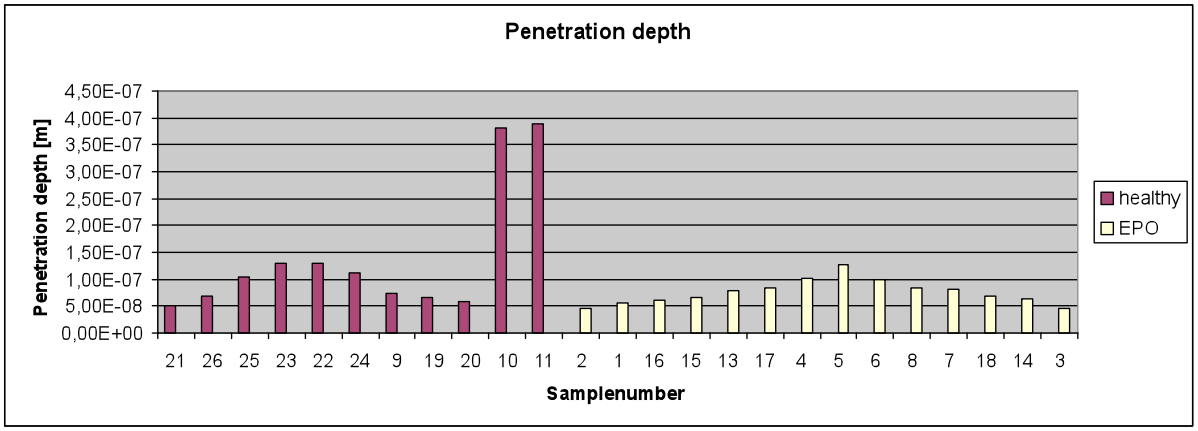

Fig. 12 Penetration depth of all 25 blood samples samples.

The AFM successfully proves as a nanodiagnostic tool. Minamitani and co-workers measured the deformability and viscoeleasticity of erythrocytes of patients with *Diabetes mellitus*, the common type of diabetes, by microchannel flow systems and atomic force microscopy. The blood cells of the patients with diabetes mellitus are harder than the control group.[73,74] The reason for the softening of erythrocytes in the rare case of diabetes presented here and the hardening of erythrocytes in diabetes mellitus is yet to be determined. Erythrocytes of people with diabetes also have a shorter live span compared to erythrocytes of a healthy control group. Currently, diabetes is diagnosed solely via chemical methods.

Biomimetic inspiration by red blood cells for architecture – results of the discussion

Transformation of principles

The most interesting characteristics of red blood cells are their shape change possibilities and the change of properties revealed in the indentation experiments presented above.

Shape change due to environmental influence

Sodium is the most important ion in the extracellular space. In hypertone dehydration one looses more water than sodium, and the concentration of ions in the extracellular space is larger than inside the erytrocytes. Water leaves the red blood cells, and the erytrocytes shrink (Fig. 13d). If the sodium concentration in the extracellular space is smaller than inside the erytrocytes, water moves into the erytrocytes and they bulge. This can happen e.g. if one drinks too much distilled water – in this case the erytrocytes can even burst.

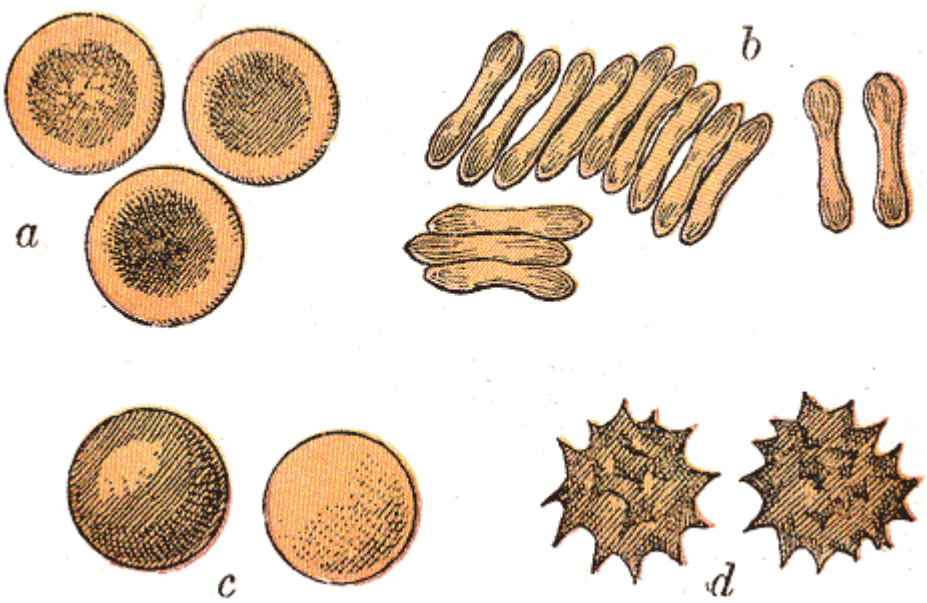

Fig. 13 a) Regular erythrocytes, **b)** Stack of erythrocytes, **c)** bulged erythrocytes **d)** thorn apple shape. Image source: Gray's anatomy of the human body, 20th U.S. edition, 1918. Public domain material.

The most interesting question; is the shape change of the red blood cells also functional? Does the change of form help to cope with potentially dangerous situations of the organism? As far as we know, there is no functional reason discovered yet.

Shape change due to environmental influence is the abstract phenomenon that is interesting for technical application. In the case of red blood cells the concentration of a specific substance triggers a radical change of form (Fig. 13). In architecture, changes of environmental conditions, for example temperature difference between inside and outside, or the presence of toxic substances in the air outside, could be used to initiate a functional form change – for example by reducing the exposed surface area. More interesting is adaptability on a materials scale. Thermal insulation is a large and expensive issue in building construction. Currently we tend to increase thermal insulation to an extent that prevents the use of the free energy from outside. Adaptability would be a solution for the daily and seasonal changes of requirements. A shape changing layer in a composite wall could react to humidity of temperature difference by increasing the layer thickness, thus increasing the air layer and insulation properties. This layer does not have to be continuous. Single points of shape changing material would be sufficient. Passive mechanisms would avoid the use of additional energy for the adaptation control - energy efficiency by passive adaptation to environmental conditions.

Another materials application is the use of the shape change principle for a sensor. The microscale reaction to environmental change could bring a macroscopic reaction with it that could be sensed by humans, for example colour change.

The change of properties

The change of properties of the red blood cells is not easy to handle, as the phenomenon is quite new. The indentation method does not deliver structural information. If we knew more about the structure we could suggest a way to change surface characteristics of materials. The adaptation of material properties, in this case hardness and softness, would be a wonderful thing to have in built environment.

Change of blood pressure is the macroscopic effect of the shape change of the red blood cells. Change of flow properties by shape changing particles – could find technical application. If we had particles

that could change shape on command, we could use them as flow control mechanism. A passive version could be: if the flow of a fluid full of particles becomes too fast and turbulent, the particles lose shape and break the flow, if the flow is slow enough again, the particles change back into initial shape.

3.III. Diatoms and Euglena gracilis

Biomimetic inspiration by diatoms for architecture – results of the discussion

Transformation of principles

The most interesting characteristics of diatoms are the fact that they biomineralize amorphous silica, the connections they establish between sibling cells and their resting stages and resting spores.

Biomineralization

Biomineralization is the process by which living organisms produce minerals, often to harden or stiffen existing tissues. Examples include silicates in algae, carbonates in diatoms and invertebrates, and calcium phosphates and carbonates in vertebrates. These minerals often form structural features such as sea shells and the bone in mammals and birds. Organisms have been producing mineralized skeletons for the past 550 million years. Other examples include copper, iron and gold deposits involving bacteria. Organisms biomineralize more than 50 different minerals such as SiO_2 and $CaCO_3$ [75].

Linking structures - connections

Some diatoms grow in colonies, the single cells are connected to each other (Fig. 14). Why are there four posts in Fig. 8 and not three? If I had two connections I could still bend the structure. Three would be enough for the reduction of the degrees of freedom. The connections shown in Figs. 8, 15 and 16 provide a certain distance, yet keep the cells together. The connections may function as dampers.

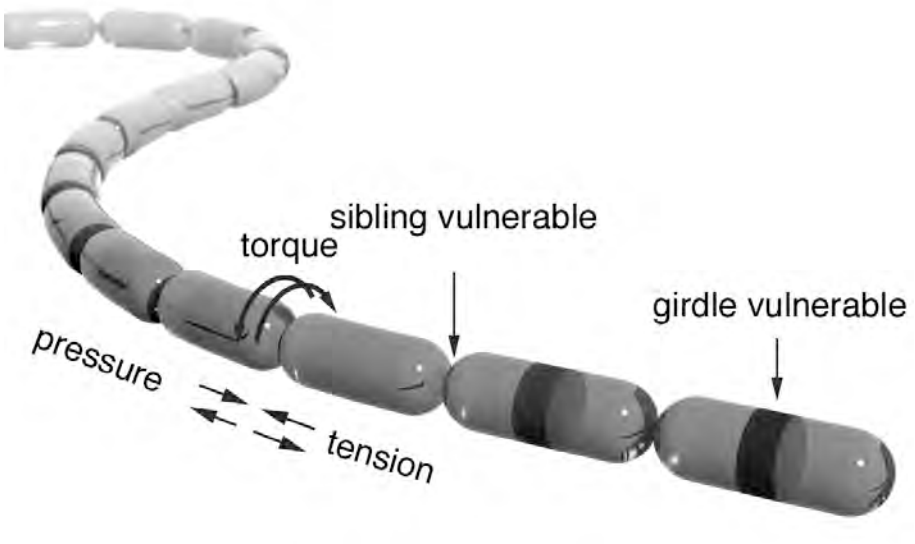

Fig. 14 Many diatoms grow in chains. The single cells are connected via junctions. The junctions can be mucilage pads, fused extensions of the cell walls, interlocking spines of varying complexity and size fitting to each other like a key to its lock or ball-and-socket arrangements.[76] © 2006, Sibirian branch of the Russian Academy of Sciences.

As can be seen below and in Figs. 15 and 16, different amounts degrees of freedom are obviously possible for different species of algae. In spite of that, they may fulfill the same function – generate space between the cells, but hold the cells together, and allow some movement between the cells.

Single linkage structure connecting siblings – single extension intertwined with neighboring one, the distance can change. Something that appears to have escaped notice until recently[77] was that although considerable movement along the connecting axis is possible, such an arrangement cannot be rotated. This is most easily appreciated by clasping one´s forearm with both hands and attempting to rotate one arm. Examples for having a single linking structure comprise species of the genera *Rutilaria* (Fig. 15) and *Syndetocystis*.

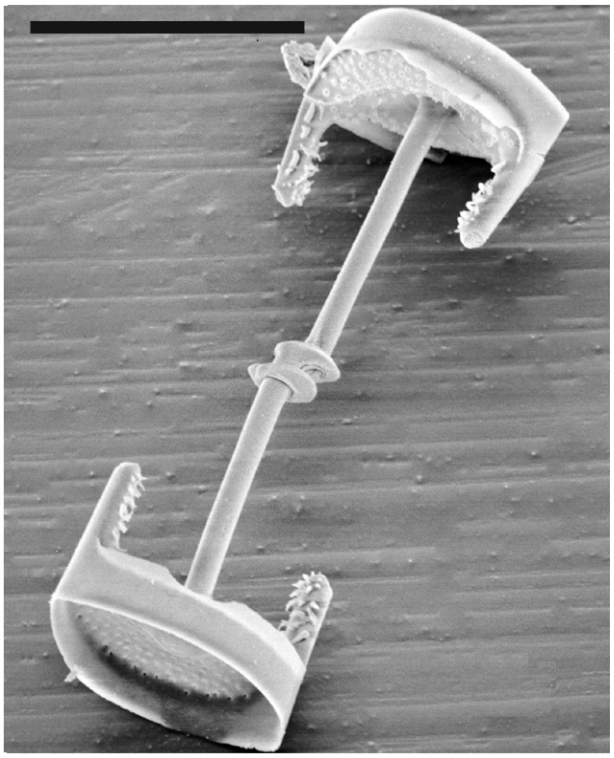

Fig. 15 Single linkage structure in *Rutilaria*. Scale bar 50 μm. © R.M. Crawford and P.A. Sims.[78]

Two linking structures connecting siblings – *Maluina* in Fig. 16 has two extensions meet in a connection that is very similar to *Solium exsculptum*. The distance is fixed, only very little movement is possible, perhaps bending in cross section is still possible. The linking structures outside look as if they are a system that reacts to compression – like a bumper. The inside looks as if they react to tension, with interdigitating "fingers", altogether hints to a semi-rigid connection, exposed to pressure and tension. On the outside of the connection area, the shell is perforated in a regular way. The function of these openings is unclear – as the material itself is not flexible, the perforated area can not deliver damping characteristics, but is still less strong than the connecting bumpers and fingers. The openness hints to exchange of something, maybe soft cell material.

Species of the genera *Maluina*, *Hemiaulus*, *Climacodium, Keratophora* and *Briggera* are examples for having two linking structures.

Three linking structures connecting siblings. *Trinacria regina* is an example for having three linking structures.

Four linking structures connecting sibling. *Solium exsculptum* in Fig. 8 has four connections at a fixed distance and position between neighboring cells. Only straight large scale colonies seem possible. *Solium exsculptum* (Fig. 8) and the *Trinacria* species presented in Crawford and Sims,

2008[78] (this species has tapering linking structures at each of the four elevations that may pull apart without damage) are examples.

Five linking structures connecting sibling. *Solium pentagona.*

Many linking structures. Most of the genera showing linking structures between sibling cells have many linking structures, attaching the cells firmly or not so firmly, holding them at a distance, some are easily separable, some not, here a lot of analysis has to be performed. However, in most of the cases the spines allow no movement of the two sibling valves *vis à vis* one another. The genera *Skeletonema*, *Stephanopyxis*, *Lamyloseira*, *Aulacoseira*, *Cymatoseira*, *Strangulonema*, *Plagiogrammopsis*, *Fragilarimforma*, *Fragilaria*, *Staurosirella*, *Staurosira*, *Preudostaurosira* and *Punetastriata* exhibit such multiple linking structures.

Many linking structures, ball-and-socket like. *Kisseleviella*.

Q: Interesting would be: is there evolutionary sequence of this functional solution?

A: In general, the connections become more complicated the more recent in the fossil record one looks, but that there are examples of "primitive" linking features in species that appeared later and even among living diatoms.[78]

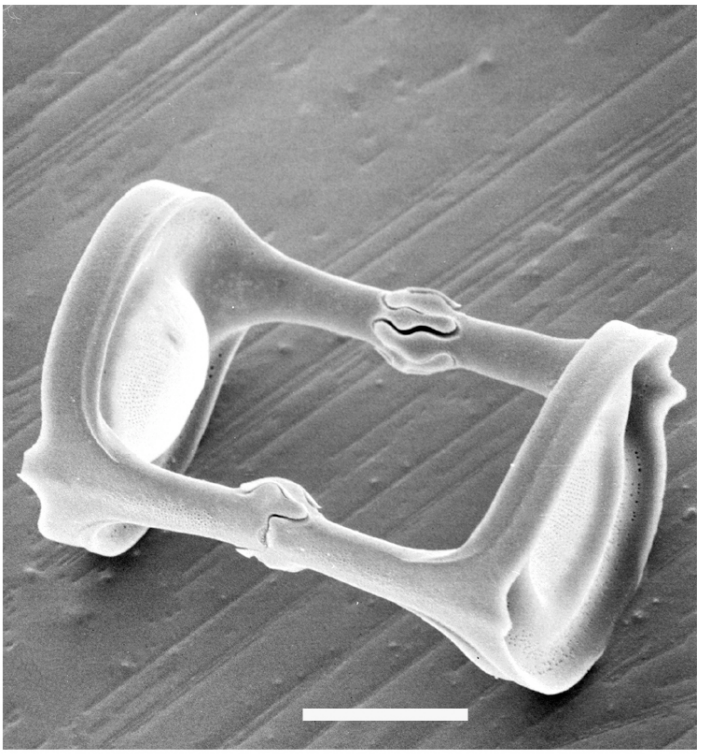

Fig. 16 Two linkage structures in *Maluina*. Scale bar 20 μm. © R.M. Crawford and P.A. Sims.[78]

Structure of *Solium exsculptum*

The most obvious characteristic about the structure of *Solium exsculptum*, its rectangular shape, can not be explained yet.

Between the main ribs the silica structure is extremely thin and interspersed with pores. In these fragile plate-like structures, secondary stiffening by small, undirected ribs can be observed. These reinforcement structures prevent the buckling that flat shells elements are prone to. There are no reinforcement ribs on the top and bottom part of *S. exsculptum* - the cytoplasm might provide enough mechanical support. The flange structure around the rim, which obviously belongs to the primary structure, is interesting – perhaps it helps in the attachment of the valves or serves as an attachment

structure for the cell membrane (Fig. 8). Altogether the structural differentiation is very material efficient.

The primary structure of *S. exsculptum* consists of the dark areas that can be distinguished in Fig.8 (for sketch see Fig. 17). These are reinforcement ribs, delivering the main force transmission areas. In the primary structures there are no holes in the amorphous silica (Fig. 17). But there are reinforcement ribs. The whole structure is made from thin material. Plates or shells without ribs would be prone to buckling. The silica structure might be so thin since many pores are needed; the mechanical stiffness comes from the reinforcements ribs. Less material is needed if thin material and reinforcements ribs are used. There are no reinforcement ribs on the top and bottom part of the *Solium* image – only the holes. Inside this top and bottom parts resides the cytoplasm, it might provide enough mechanical support to prevent mechanical damage.

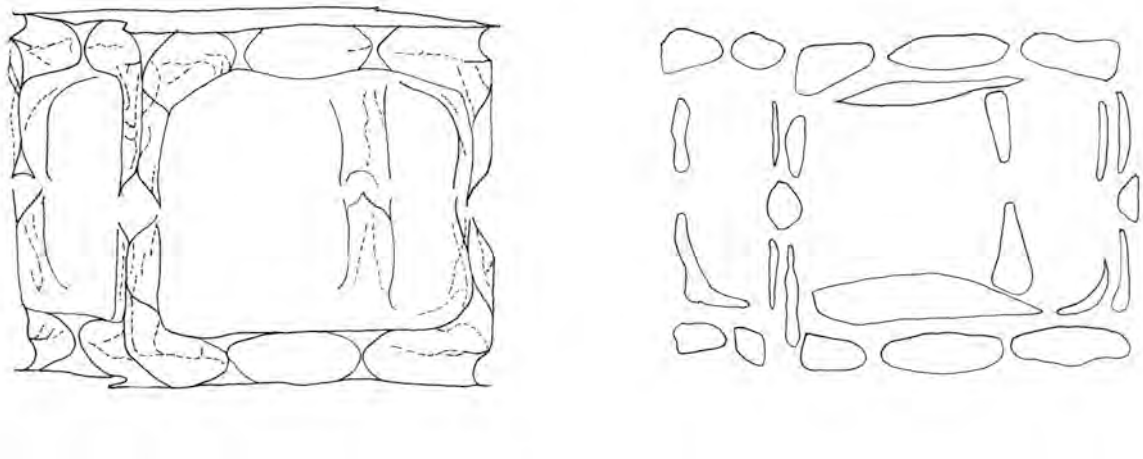

Fig. 17 left: Primary structure of *Solium exsculptum*, as far as discernable. Dark regions interpreted as reinforced main structural elements. Dashed lines indicate secondary ribs, reinforcing the thin plates. **right:** Scheme of approximate extension of thin plates, enabling exchange by interspersed holes.

Spore formation.

Some diatoms, especially those whose natural habitats are soil and rock, can survive desiccation for decades. Dormant vegetative cells, resting stages and resting spores ensure survival.[79]. Diatom resting spores (hypnospores) are heavily silicified stages in the life cycles of marine centric diatoms and a few freshwater and pennate diatoms.[80,81,82,83] In some genera, resting spores superficially resemble the parent vegetative cell, whereas in others, spores and vegetative cells are morphologically quite different.

Biomimetic inspiration by *Euglena gracilis* for architecture – results of the discussion

Transformation of principles

The most interesting characteristics of the *Euglena* are its sensing and orientation system, together with its movement and skin structure.

Integrated orientation and locomotion system

Locomotion and sensing are combined functions within one complex "organ". The rotational movement initiated by the flagellum is used for periodic shielding of the sensing device in order to deliver a signal difference that is interpreted directly and defines the overall direction of movement.

The same principle works with other than light signals.

Orientation in space is essential for all living organisms. Human orientation depends on signal difference between pairs of sensing organs, and locomotion is as important for orientation. In contrast to common knowledge which accredits orientation to sight, sound is very important for spatial orientation.

Technical devices for orientation in space already exist, for example the GPS system. It depends on signal contact to a range of satellites. The easy availability of those systems for private use has already influenced our perception of built environment and our behaviour.

Spatial orientation is not sufficient for human survival in complex environment. Orientation in architecture and in built environment in general, is not always easy. Large buildings, for example hospitals, traffic infrastructure, etc. need signage to transfer information to the users, which has to be applied or inserted into the built environment. Another system, providing selective information when needed would be helpful. The visibility of pathways taken by other people, following the principle of chemical tracing of ants, could be helpful for finding one's way. I could also use state transitions to activate something, e.g. a path to an exhibition gets bright if many people walk on it. This would yield reactive illumination in buildings, on floors, on streets and new concepts for illuminating streets, parks, halls, etc.

Storage medium

The crystals inside the sensing organ of *Euglena* provide a switch triggered by light. This change in state of rhodopsin could be exploited, or transferred to another nanoscale system, which delivers a similar effect.

This could be implemented into surface materials to detect the presence of people, initiated for example by touch or acoustics. Another example would be reactive shirts for soccer players that indicate fouls by being pulled by a change of colour (the more pull the more intense the color).

The principle could as well be transferred to a larger scale system, monitoring something happening in a "sensing material" that also delivers information to the environment.

Skin structure of Euglena

Skin structure built from inside

A protein layer builds up the skin of *Euglena* from the inside. This method of growth is interesting as it could be transferred to a light and soft system forming space in synthesizing material and structure from inside out. The delivery of material works easily in liquid solution, but would have to be solved in a different way in air. The interior system would have to be stable enough to maintain itself and integrate a transport system for the material. Inside out technologies could be interesting for rapid prototyping or production technologies.

Skin structured in stripes

The outer skin of *Euglena* is structured in stripes. One of the biggest challenges that are currently explored in architecture is the construction of complex shapes with (mostly) two-dimensional flat material. The conservative building industry is still working based on two dimensions, but new production technologies allow three-dimensional material processing.

With two-dimensional stripes of material one can generate open geometries (cylinders), but for having more complex, three-dimensional curved shapes the stripes would need to deform, change width and taper off to zero – all this to achieve a static form. Change of cross-sectional geometry of the stripes themselves would be another way of solving this.

Flexibility of the material itself enables a specific amount of change already, but other mechanisms exist in *Euglena* that allowing not only for adaptability but also active locomotion.

Flexibility of connection

The connection of the skin-stripes is very interesting from a functional/geometric point of view. A model would help to understand the functionality of and the options provided by the connection. It is perhaps useful for the development of a new connection system of cladding material, or even useful as a model for the connections of monocoque elements.[1] The first association of a biologists to transfer the principle to a technical membrane must fail - „soft“ membranes are pre-stressed to maintain stability under different loading conditions. A rigid frame would have to be used where a soft membrane could be attached to.

Movement mechanism

The stripes of the shell move along each other. There are decentralised „motors“ along the connection. This could be translated into a decentralised actuation system, allowing an architectural skin to adapt according to specific stimuli. An integrated actuation system like this would be very useful for adaptable folded structures. Integrated actuation would allow a system to deploy without centralised control.

Movement and complex geometry

Movement AND complex geometry seem currently impossible to achieve in an architectural solution.

The analysis of the overall system of *Euglena* could provide a new approach to solutions for adaptability in building skin. Useful information to have would be the relation of the scale of deformation of the skin stripes to the movement along the stripes. An analysis of overall geometric changes and a model would be helpful to fully understand the process.

4. Interpretation, Conclusions and Outlook

An overview with the organism examples and phenomena interesting for transfer from bionanotechnology to architecture is given in Table 1. Several criteria and aspects important for the specific example are described, and estimated values for transfer issues like scaling and grade of abstraction are provided.

The novel approach attempted in this book chapter turned out to be fruitful for both sides. The bionanotechnologists and the architects got input concerning the applicability of reserach results and future research directions. This approach should be intensified and extended to other fields. The newly erected Center of Excellence TU BIONIK at the Vienna University of Technology (comprising 30

[1] Monocoque (French for "single" (mono) and "shell" (coque)) is a construction technique that supports structural load using an object's external skin. This stands in contrast with using an internal framework (or truss) that is then covered with a non-load-bearing skin. Monocoque construction was first widely used in aircraft, starting in the 1930s.

researchers from eight faculties) and other similar centers such as the BIONIS network in the UK or the BIOKON network in Germany provide the experts and the interdisciplinarity that is needed.

Current challenges in architecture that shall be met with the help of nanotechnology are:

- Functional integration to improve durability and provide new functions for building elements, for example multifunctional facades, providing optimum light conditions and protection against corrosion, fungi and vandalism.
- Improvement of customer convenience, changes in social and urban structures will have to be dealt with, for example concerning safety issues.
- The need for material and energy efficiency, together with increasing environmental consciousness, will be important triggers for change.
- Increasing activation of building elements requires integration of new functions like sensing and actuation, for example according to environmental conditions.

	organism	**bacili**		**green algae**		**diatoms**		**red blood cells**
	phenomena / transfer	sporulation	structure of membrane	sensing and orientation device	structure of skin	structure	connections	shape change
kind of phenomenon	process	sporulation		direct information transfer of sensing to locomotion	generation from inside out	"casting" process		osmotic process
	system			orientation device				
	material				proteins	silica	silica	
	structure		regional differences		s shaped stripes	lightweight	lightweight	
aspects	integration			sensing and locomotion	actuation			
	differentiation		surface properties		stripes	structural differentiation	structural differentiation	
	locomotion			locomotion by flagellar movement	locomotion by shape change		connection defines colony locomotion	changes due to shape change
	adaptibility	sporulation due to external environment	evolutionary adaptibility to UV		shape change			shape change due to external environment
	form / geometry		patterned properties		form of stripes			
transfer issues	scaling possible	yes	no	no	yes	yes	yes	yes
	grade of abstraction	****	***	****	**	*****	*	*****
	* low	***** high						

Table 1 Overview with organism examples and phenomena interesting for transfer. Several criteria and aspects important for the specific example are described, and estimated values for transfer issues like scaling and grade of abstraction are provided.

Acknowledgements

Part of this work has been funded by the Austrian K*plus*-Program via the Austrian Centre of Competence for Tribology, AC^{2}T research GmbH,Wiener Neustadt.

The authors thank R.M. Crawford and F. Hinz for the permission to use images and for fruitful discussions and provision of literature.

References

[1] Gebeshuber I.C. (2007) "Biotribology inspires new technologies", invited article, Nano Today 2(5), 30-37, doi:10.1016/S1748-0132(07)70141-X

[2] Gebeshuber I.C. and Drack M., invited article, "An attempt to reveal synergies between biology and engineering mechanics", IMechE Part C: J. Mech. Eng. Sci., in press

[3] Gruber P. (2008) "Biomimetics in Architecture [Architekturbionik] – the architecture of life and buildings", Doctoral thesis, Vienna University of Technology

[4] Leydecker S. (2008) „Nanomaterialien in Architektur, Innenarchitektur und Design", Birkhäuser Verlag AG, Basel - Boston - Berlin.

[5] VDI (Ed.), Luther W. and Zweck A. (2006) „Anwendungen der Nanotechnologie in Architektur und Bauwesen", Zukünftige Technologien Consulting der VDI, Düsseldort, 2006.

[6] Barthlott W. and Neinhuis C. (1997) "The purity of sacred lotus or escape from contamination in biological surfaces", Planta 202, 1-8.

[7] Lee E. (2006) "A design guide for early market electrochromic windows" for California Energy Commossion, PIER Program Contract No. 500-01-023

[8] Lampert A. (1980) "Thin film electrochromics for energy efficient windows" for U.S. department of Energy on Contract No. DE-ACO3-76SF00098

[9] Boden S.A. und Bagnall D.M. (2006) "Bio-mimetic subwavelength surfaces for near-zero reflection sunrise to sunset", Proc. 4th IEEE World Conference on Photovoltaic Energy Conversion, Hawaii, 1358-1361.

[10] Vukusic P. und Sambles J.R. (2003) "Photonic structures in biology", Nature 424, 852-855.

[11] Schaefer D.W. and Keefer K.D. (1986) "Structure of random porous materials: silica aerogel", Phys. Rev. Lett. 56, 2199-2202.

[12] Dufrêne Y.F. (2002) "Atomic force microscopy, a powerful tool in microbiology", J. Bacterol. 184(19), 5205-5213.

[13] Magonov S.N., Proctor C.S., Whangbo M.H. (1989) "Phase imaging and stiffness in tapping mode atomic force microscopy", Surf. Sci. 375, 385-391.

[14] Savage D.C. and Fletcher M. (1988) "Bacterial adhesion", Plenum Press, New York, 140-200.

[15] Beveridge T.J. and Graham L.L. (1991) "Surface layers of bacteria", Microbiol. Rev. 55(4), 684-705.

[16] Mozes N., Handley P.S., Busscher H.J. and Rouxhet P.G. (1992) "Microbial cell surface analysis: structural and physicochemical methods", J. Dispers. Sci. Technol. 13(1), 115-117.

[17] Kasas S., Fellay B. and Cargnello R. (1994) "Observation of the action of penicillin on *Bacillus subtilis* using atomic force microscopy. Technique for the preparation of bacteria", Surf. Interface Anal. 21(6), 400-401.

[18] Nicholson W.L., Munakata N., Horneck G., Melosh H.J. and Setlow P. (2000) "Resistance of Bacillus endospores to extreme terrestrial and extraterrestrial environments", Microbiol. Rev. 64(3), 548-572.

[19] Hörber J.K. (2006) "Adapting AFM Techniques for studies on living cells", In: Force microscopy, applications in biology and medicine (eds: Jena B.P. and Hörber J.K.H.), 137-158.

[20] Singhvi R., Kumar A., Lopez G., Sephanopoulos G.N., Wang D.I., Whiteside G.M. and Ingber D.E. (1994) "Engineering cell shape and function", Science 264(5159), 696-698.

[21] Yao X., Jericho M., Pink D. and Beveridge T. (1999) "Thickness and elasticity of gram-negative murein sacculi measured by atomic force microscopy", J. Bacteriol. 181(22), 6865-6875.

[22] Hekele O. and Goesselsberger C.G. (2006) "AFM force mapping on healthy and EPO red blood cells", project work, Technische Universität Wien, Institut fuer Allgemeine Physik

[23] Cross S.E., Jin Y.-S., Rao J. and Gimzewski J.K. (2007) "Nanomechanical analysis of cells from cancer patients", Nature Nanotechnology 2, 780-783.

[24] Dulińska I., Targosz M., Strojny W., Lekka M., Czuba P., Balwierz W. and Szymoński M. (2006) "Stiffness of normal and pathological erythrocytes studied by means of atomic force microscopy", J. Biochem. Biophys. Meth. 66(1-3), 1-11.

[25] Nicholson W.L., Munakata N., Horneck G., Melosh H.J., Setlow P. (2000) "Resistance of *Bacillus* endospores to extreme terrestrial and extraterrestrial environments", Microbiol. Rev. 64(3), 548-572.

[26] Nagao E. and Dvorak J.A. (1999) "Phase imaging by atomic force microscopy: analysis of living homoiothermic vertebrate cells", Biophys. J. 76(6), 3289-3297.

[27] Magonov S.N., Proctor C.S. and Whangbo M.H. (1989) "Phase imaging and stiffness in tappingmode atomic force microscopy", Surf. Sci. 375, 385-391.

[28] Sommer R., Cabaj A., Sandu T. and Lhotsky M., (1999) "Measurement of UV radiation using suspensions of microorganisms", J. Photochem. Photobiol. B: Biol. 53(1-3), 1-6.

[29] Rosati G., Verni F., Barsanti L., Passarelli V. and Gualtieri P. (1991) "Ultrastructure of the apical zone of *Euglena gracilis*: photoreceptors and motor apparatus", Electron Microsc. Rev. 4, 319-342.

[30] Gruenberger C., Ritter R., Aumayr F., Stachelberger H. and Gebeshuber I.C. (2007) "Algal biophysics: *Euglena gracilis* investigated by atomic force microscopy", Mat. Sci. Forum 555, 411-416.

[31] Gruenberger C. (2007) "Atomic force microscopy of the alga *Euglena gracilis*", diploma thesis, Institut fuer Allgemeine Physik, Vienna University of Technology.

[32] Leedale G.F. (1967) "Euglenoid flagellates", Englewood Cliffs, N.J., Prentice-Hall.

[33] Rosati G., Verni F., Barsanti L., Passarelli V. and Gualtieri P. (1991) "Ultrastructure of the apical zone of *Euglena gracilis*: photoreceptors and motor apparatus", Electron Microsc. Rev. 4, 319-342.

[34] Trebbels D. (2002) "Die Protozoen", PDF-file

[35] Barsanti L., Passarelli V., Walne P.L. and Gualtieri P. (2000) "The photoreceptor protein of *Euglena gracilis*", FEBS Letters 482(3), 247-251

[36] Schoenlein R.W., Peteanu L.A., Mathies R.A. and Shank C.V. (1991) "The first step in vision: femtosecond isomerization of rhodopsin", Science 254, 412-415.

[37] Dubreuil R. and Bouck G. (1985) "The membrane skeleton of a unicellular organism consists of bridged, articulating strips", J. Cell Biol. 101, 1884-1896.

[38] Rosiere T.K., Marts J.A. and Bouck G.B. (1990) "A 39-kD plasma membrane protein (IP39) is an anchor for the unusual membrane skeleton of *Euglena gracilis*", Dep. Biol. Sci., Univ. Illinois at Chicago, Chicago, Illinois

[39] Round F.E., Crawford R.M. and Mann D.G. (2007) "Diatoms: Biology and morphology of the genera", Cambridge University Press, Cambridge

[40] Smith, B.L., Schaeffer, T.E., Vlani, M., Thompson, J.B., Frederick, N.A., Kindt, J., Belcher, A., Stucky, G.D., Morse, D.E. and Hansma, P.K. (1999) "Molecular mechanistic origin of the toughness of natural adhesives, fibres and composites", Nature 399, 761-763.

[41] Werner D. (1977) "The biology of diatoms", University of California Press, Berkeley.

[42] Gordon R. and Drum R.W. (1994) "The chemical basis for diatom morphogenesis", Int. Rev. Cytol. 150, 243-372.

[43] Gebeshuber I.C. Stachelberger H. and Drack M. (2004) "Surfaces in relative motion: bionanotribological investigations", In: First International Industrial Conference Bionik (eds. Boblan I. and Bannasch R.), Fortschr.-Ber. VDI Reihe 15(249), VDI Verlag, Düsseldorf, 229-236.

[44] Gebeshuber I.C., Stachelberger H. and Drack, M. (2005) "Diatom bionanotribology-biological surfaces in relative motion: Their design, friction, adhesion, lubrication and wear", J. Nanosci. Nanotechnol. 5, 79-87.

[45] Gebeshuber I.C., Stachelberger H. and Drack M. (2005) "Diatom biotribology", Tribol. Interface Eng. 48, 365-370.

[46] Crawford R.M. and Gebeshuber I.C. (2006) "Harmony of beauty and expediency", Science First Hand 5, 30-36.

[47] Gebeshuber I.C. and Crawford R.M. (2006) "Micromechanics in biogenic hydrated silica: Hinges and interlocking devices in diatoms", Proc. IMechE Part J: J. Eng. Tribol. 220, 787-796.

[48] Gebeshuber I.C., Stachelberger H. and Drack, M. (2005) "Diatom bionanotribology-biological surfaces in relative motion: Their design, friction, adhesion, lubrication and wear", J. Nanosci. Nanotechnol. 5, 79-87.

[49] Gebeshuber, I.C., Thompson, J.B., Del Amo, Y., Stachelberger, H. and Kindt J.H. (2002) "*In vivo* nanoscale atomic force microscopy investigation of diatom adhesion properties", Mat. Sci. Technol. 18 (2002), p. 763-766.

[50] Parkinson J. and Gordon R. (1999) "Beyond micromachining: The potential of diatoms", Trends Biotechnol. 17, 190-196.

[51] Gebeshuber I.C., Kindt J.H., Thompson J.B., DelAmo Y., Brzezinski M., Stucky G.D., Morse D.E. and Hansma P.K. (1999) "Atomic force microscopy of diatoms *in vivo*", in: Abstracts of the 15th North American Diatom Symposium, (eds. Spaulding S. and Kingston J.), Pingree Park Campus, Colorado State University, September 1999, 8.

[52] Gebeshuber, I.C., Thompson, J.B., Del Amo, Y., Stachelberger, H. and Kindt J.H. (2002) "*In vivo* nanoscale atomic force microscopy investigation of diatom adhesion properties", Mat. Sci. Technol. 18 (2002), p. 763-766.

[53] Crawford S.A., Higgins M.J., Mulvaney P. and Wetherbee R. (2001) "Nanostructure of the diatom frustule as revealed by atomic force and scanning electron microscopy", J. Phycol. 37, 543-554.

[54] Gebeshuber I.C., Kindt J.H., Thompson J.B., Del Amo Y., Stachelberger H., Brzezinski M.A., Stucky G.D., Morse D.E. and Hansma P.K. (2003) "Atomic force microscopy study of living diatoms in ambient conditions", J. Microscopy 212, 292-299.

[55] Higgins M.J., Crawford S.A., Mulvaney P. and Wetherbee R. (2002) "Characterization of the adhesive mucilages secreted by live diatom cells using atomic force microscopy", Protist 153, 25-38.

[56] Higgins M.J., Molino P., Mulvaney P. and Wetherbee R. (2003) "The structure and nanomechanical properties of the adhesive mucilage that mediates diatom-substratum adhesion and motility", J. Phycol. 39, 1181-1193.

[57] Higgins M.J., Sader J.E., Mulvaney P. and Wetherbee R. (2003) "Probing the surface of living diatoms with atomic force microscopy: The nanostructure and nanomechanical properties of the mucilage layer", J. Phycol. 39, 722-734.

[58] Special issue on diatom nanotechnology, (eds: Gordon R., Sterrenburg F. and Sandhage K.), J. Nanosci. Nanotechnol. 5 (2005), 1-178.

[59] Ross R. and Sims P.A. (1987) "Further genera of the *Biddulphiaceae* (diatoms) with interlocking spines", Bull. Brit. Mus. (Nat. Hist.) Botany Series 16(4), 269-311.

[60] Crawford R.M. and Gebeshuber I.C. (2006) "Harmony of beauty and expediency", Science First Hand 5, 30-36.

[61] Gordon R. (1996) "Computer controlled evolution of diatoms: design for a compustat" Nova Hedw. 112, 213-216.

[62] Drum R.W. and Gordon R. (2003) "Star Trek replicators and diatom nanotechnology", Trends Biotechnol. 21(8), 325-328.

[63] Sandhage K.H., Dickerson M.B., Huseman P.M., Caranna M.A., Clifton J.D., Bull T.A., Heibel T.J., Overton W.R., Schoenwaelder M.E.A. (2002) "Novel, bioclastic route to self-assembled, 3D, chemically tailored meso/nanostructures: Shape-preserving reactive conversion of biosilica (diatom) microshells", Adv. Mat. 14(6), 429-433.

[64] Cai Y., Allan S.M., Sandhage K.H. and Zalar F.M. (2005) "Three-dimensional magnesia-based nanocrystal assemblies via low-temperature magnesiothermic reaction of diatom microshells", J. Am. Ceram. Soc. 88(7), 2005-2010.

[65] Weatherspoon M.R., Allan S.M., Hunt E., Cai Y. and Sandhage, K.H. (2005) "Sol-gel synthesis on self-replicating single-cell scaffolds: Applying complex chemistries to nature's 3-D nanostructured templates", Chem. Com.5, 651-653.

[66] Bao Z., Weatherspoon M.R., Shian S., Cai Y., Graham P.D., Allan S.M., Ahmad G., Dickerson M.B., Church B.C., Kang Z., Abernathy III H.W., Summers C.J., Liu M. and Sandhage K.H. (2007) "Chemical reduction of three-dimensional silica micro-assemblies into microporous silicon replicas", Nature 446(7132), 172-175.

[67] Sommer R., Cabaj A., Sandu T. and Lhotsky M., (1999) "Measurement of UV radiation using suspensions of microorganisms", J. Photochem. Photobiol. B: Biol. 53(1-3), 1-6.

[68] Nowakowski R., Luckham P. and Winlove P. (2001) "Imaging erythrocytes under physiological conditions by atomic force microscopy", Biochim. Biophys. Acta 1514, 170-176.

[69] Nowakowski R. and Luckham P. (2002) "Imaging the surface details of red blood cells with atomic force microscopy", Surf. Interf. Anal. 33, 118–121.

[70] Lekka M., Fornal M., Pyka-Fosciak G., Lebed K., Wizner B., Grodzicki T.and Styczen J. (2005) "Erythrocyte stiffness probed using atomic force microscope", Biorheol. 42(4), 307-317.

[71] Lui F., Burgess J., Mizukami H. and Ostafin A. (2003) "Sample preparation and imaging of erythrocyte cytoskeleton with the atomic force microscopy", Cell Biochem. Biophys. 38(3), 251-270.

[72] Speck T., Harder D., Milwich M., Speck O. and Stegmaier T. (2006) „Die Natur als Innovationsquelle". In Technische Textilien (ed. Knecht P.), Deutscher Fachverlag, Frankfurt, Germany, 83-101.

[73] Minamitani H., Kawamura T., Sekizuka I., Simizu T., Tsukada K. and Oshio C. (1999) "Deformability and viscoelasticity of diabetic erythrocytes measured by microchannel flow system and atomic force microscope ", Engineering in Medicine and Biology, 1999. 21st Annual Conf. and the 1999 Annual Fall Meeting of the Biomedical Engineering Soc., BMES/EMBS Conference, 1999. Proceedings of the First Joint, Vol. 1, 72.

[74] Minamitani H., Tsukada K., Kawamura T., Sekizuka I. and Oshio C. (2000) "Analysis of elasticity and deformability of erythrocytes using micro-channel flow system and atomic force microscope", 1st Annual International Conference on Microtechnologies in Medicine and Biology, 68-71.

[75] Baeuerlein E., Behrens P. and Epple M. (eds) (2007) Handbook of biomineralization, 3 Volumes, Wiley & Sons.

[76] Crawford R.M. and Gebeshuber I.C. (2006) "Harmony of beauty and expediency", Science First Hand 5, 30-36.

[77] Gebeshuber I.C. and Crawford R.M. (2006) "Micromechanics in biogenic hydrated silica: Hinges and interlocking devices in diatoms", Proc. IMechE Part J: J. Eng. Tribol. 220, 787-796.

[78] Crawford R.M. and Sims P.A. (2008) "Some principles of chain formation as evidenced by the early diatom fossil record", Nova Hedw. Beiheft 133, 171-186.

[79] Hoban M.A., Fryxell G.A., Buck K. (1980) "Biddulphioid diatoms: resting spores in Antarctic *Eucampia* and *Odontella*", J. Phycol. 16, 591-602.

[80] Hargraves P.E. and French F.W. (1983) "Diatom resting spores: Significance and strategies", in: Survival strategies of the algae (ed. Fryxell G.A.), Cambridge University Press, Cambridge, 49-68.

[81] French F.W. and Hargraves P.E. (1980) "Physiological characteristics of plankton diatom resting spores", Mar. Biol. Lett. 1, 185-195.

[82] Hargraves P.E. and French F.W. (1975) "Observations on the survival of diatom resting spores", Nova Hedw. Beiheft 53, 229–238.

[83] Hargraves P.E. (1976) "Studies on marine plankton diatoms: II. Resting spore morphology 1", J. Phycol. 12, 119–128.