# Chapter 2
# Buildings, Architecture, and Biomimetics

The juxtaposition of structural sciences and biology leads to a multitude of—sometimes surprising—analogies. It shows primarily that the fundamental principles in both disciplines are comparable throughout. It is therefore worthwhile to peer over the fence, not simply in one direction but both.

Ecological, structurally functional, and esthetic viewpoints additionally demand a return to the old principles of construction. An "organic" shape of building is not intended, instead one that incorporates and uses natural properties. Architects of antiquity have already noted that their building volumes were embedded in a preexisting environment, compelling them to construct structures oriented to the prevailing winds (structurally functional aspect) and ultimately yielding a convincing and harmonic impression (building esthetic aspect). So-called primitive cultures followed these rules as well up until recently (ancient Iranian architecture) and still today (native architecture in some parts of Africa). These ancient cultures are therefore interesting, as their building design is "biomimetic" so to speak, namely it is completely analogous to the process of natural evolution according to its trial-and-error methods. One could not pre-calculate a complete, comprehensive structure even in the Middle Ages; Gothic domes essentially arose from trial-and-error methods.

Concrete possibilities for comparison can be found between the technological dwellings of humans and other living organisms and their structures; aspects of temperature regulation, as they are embodied in polar bear fur or solar-driven climate systems, or as they are constructed by termites, belong to these observational categories.



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## 2.1 Technical Biology and Biomimetics of Building and Load-Bearing Structures

In the following sections, forms of building structures in nature and analogous technical concepts will be juxtaposed to one another, as they have occurred in historical, physical, functional, or ecological observation.

The juxtaposition of these analogs will consist of the following seven sections, from dome-forming node-and-rod structures to the question of whether one has actually completely understood the honeycombs of honeybees and if they are in fact "technologically optimal." In the frame of these analogies, the architect B. Kresling and the biologist W. Nachtigall wrote short summaries on several subjects that could shed light on biological structuring and self-organization processes in different aspects. They are reproduced here in italicized quotations.

### *2.1.1 Dome-Forming Node-and-Rod Structures*

Structures of this type are composed of rod members (pressure and tension rods) and nodes (joints). An optimized structure works with a least possible amount of members, which ideally form a triangular mesh network and regulate the flow of forces so that the individual members are relieved of bending stress and bear only pressure and tension stresses.

The basic forms of equilateral structures of this type are three of the Platonic forms, the tetrahedron, the octahedron, and the icosahedron (Fig. 2.1a). The nodes of these structures all lie on an imaginary spherical shell. Each node is surrounded by the same number of equilateral triangles. Three members of a tetrahedron, or four in the case of the octahedron or five in the icosahedron ("basic frequency," "frequency one"), connect to one node. If one were to subdivide the resulting triangle further (Fig. 2.1a), the resulting connecting members would no longer lie on the same sphere but on an "inner" sphere.

In such domes several members surround a node, namely five or six ("higher frequencies"). One can also say that the base triangles are subdivided into several meshes and these are "exploded" onto a spherical form. Analog biological structures possess up to seven members meeting at one node (Fig. 2.1b).

The sphere form as such is of course completely symmetrical. In contrast, if one were to lay a fine mesh network over it, two types of nodes would emerge and therefore a reduced number of symmetry planes. Particularly irregular meshes with a relatively large number of members per node are found in biology. These are often interpreted as "mistakes;" they can however also imply that dynamic self-organization processes have taken place, which would then suggest a functional or mechanical meaning.

In contrast to technical, spherical meshworks, which are from the beginning "rigidly" arranged (Fig. 2.1c) and cannot be expanded in volume or easily modified,

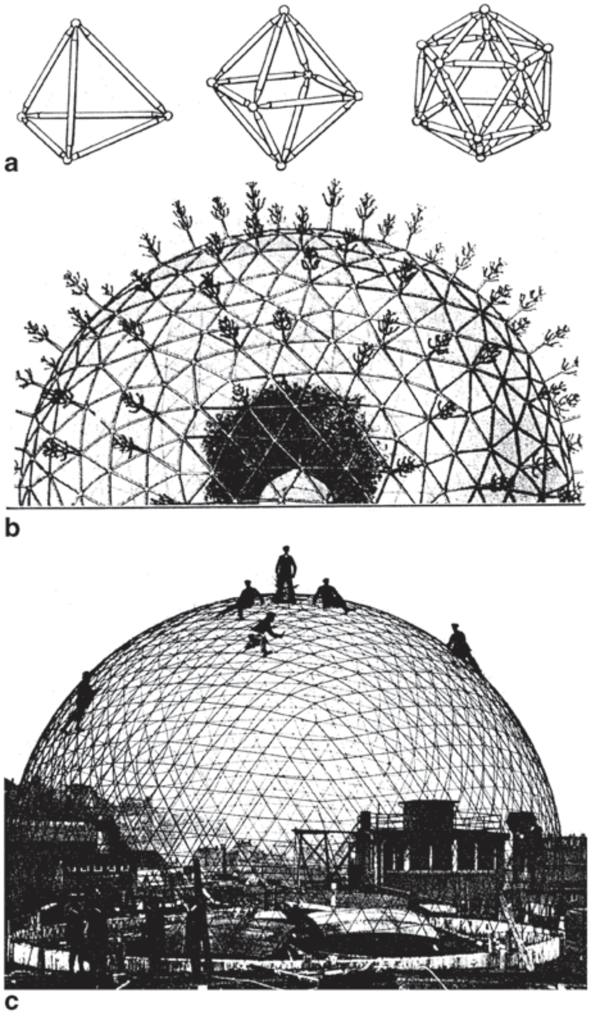


**Fig. 2.1** Dome-forming node-and-rod structures in nature and in architecture. **a** Platonic forms, members of the same length complete a triangle. **b** Biological sphere network with dissimilar member lengths: silicate skeleton of the radiolarian *Aulosphaere spec.* (Haeckel 1899). **c** Architectural sphere network with members of equal length: first planetarium of Zeiss, Jena

a "natural" spherical form—for example, that of the radiolaria—must be able to morph and adjust. It rotates conceivably around a center of gravity that is often not quite centered. When that is the case, it slightly deviates from the spherical form and becomes somewhat irregular and instable.

## 2.1.2 Special Forms of Spatial Node-and-Rod Structures

The spherical-appearing radiolaria often carry one to several hollow spheres within one another, which had been formed earlier. In the formation process each new shell depends on radial braces called spicules. The individual members grow outward from these dependency points toward each other and ultimately fuse together into a spherical entity. This construction principle is possible only with a node-and-rod structure that is subtly instable (Fig. 2.2a). Structural stability is reached after the fusion of members by a thickening of the members and nodes, transforming into a sort of panel structure. The formation of a spherical shell is then complete.

The French engineer Robert Le Ricolais used the drawings of radiolaria by E. Haeckel and V. Haecker as an opportunity to produce experimental models for spatial structures according to the principle of radiolaria skeletons. In his first designs, he worked with a double-layered hexagon mesh grid, which is strengthened by diagonal members that jut out from above and below a middle layer (Fig. 2.2b); reaching a sort of proto form that is not yet completely stable. This structure can be later modified in various ways and further developed into a fully stable structure.

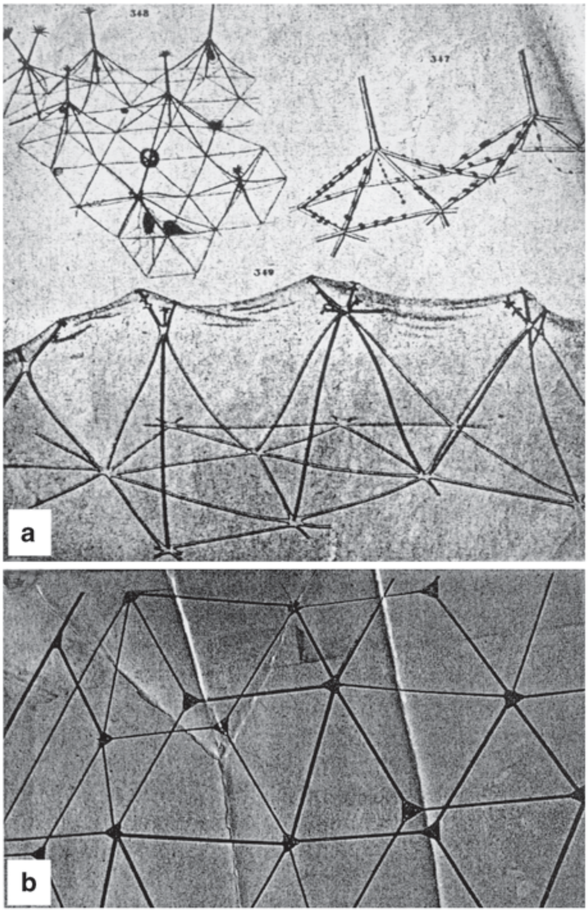


**Fig. 2.2** Forms of spatial node-and-strut structures in nature and architecture. **a** Detail of the silicate skeleton of radiolaria. **b** Early three-dimensional dome modeled according to the *Sargoscena* precedent, original photo: R. Le Ricolais, ca. 1935 (Adapted from Nachtigall and Kresling 1992a)

### 2.1.3 Self-supporting Structures ("Tensegrity Structures")

Le Ricolais had already suggested that the structure of radiolaria does not represent a pure truss framework but a structural hybrid of a frame and supportive cladding. One designates structures that support themselves as "tensegrity" structures (R. B. Fuller), in French as "structures auto-tendantes" (D.G. Emmerich). They consist of building elements that are supported on either tension (pull wires) or pressure (freely suspended and untouching pressure rods) (Fig. 2.3b) but not both. A. Chassagnoux, a student of Emmerich, suggested that the smallest irregularities in the tensions of the cables result in a warping of the structure. Theoretically, several shifted variations are possible for a spatial entity, which means differing from the ideal geometrically defined form based on the center of mass. Instead they oscillate so to speak around the center.

Analogous biological structures are represented, for example, by sea radiolaria from the group of the Acantharea (Fig. 2.3a). Tension elements are here again

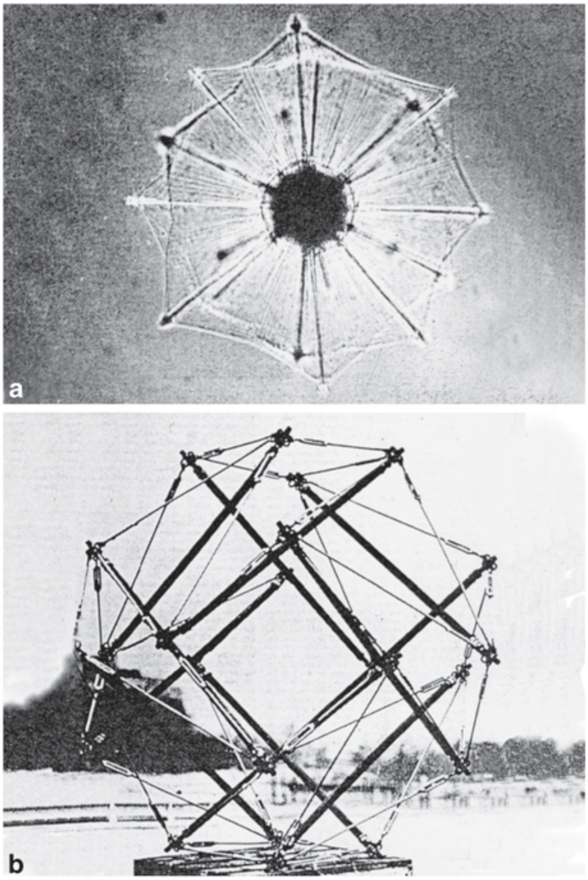


**Fig. 2.3** Self-supporting structures ("tensegrity structures") in nature and architecture **a** Sea radiolarian of the group Acantharia with skeleton of strontium sulfate (Courtesy of C. Carre). **b** Tension wire-pressure rod "tensegrity" structure by G. Emmerich

braced with radial, compression-resistant spines, which can also be augmented. The outer membrane in its totality forms the biological equivalent to the tension elements. For this purpose, the tension work performed by the "cables" automatically "adjusts" to the straight growing, pressure-bearing spines.

### *2.1.4 Orthogonal Lattice Structures*

One finds stunningly consistent and—which concerns each idealized axis—nearly rectangular lattice structures in the walls of the tubelike glass sponge (Fig. 2.4a). They consist of membranes in which star-shaped spikes are suspended. These spikes bear six arms in the directions of the three spatial axes toward which they can grow to meet other arms and fuse together into the orthogonal lattice structures of the matured sponge. Before fusing, the spikes often shift and orient themselves repeatedly anew; they "wander" in the rhythm of the active tensing and slackening movements of the membrane. As soon as the spikes have organized into an orthogonal grid network however, bending stress occurs in the nodal points, which causes the nodes to strengthen themselves. Additional spines are also formed afterward

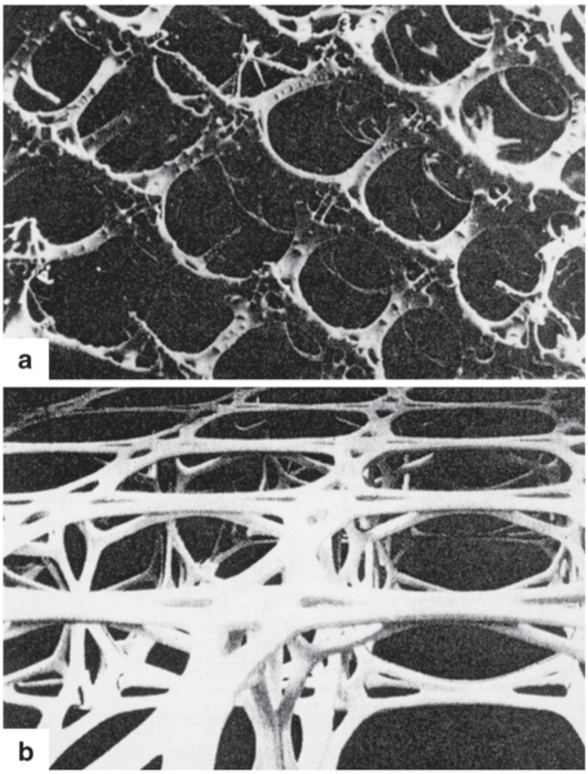


**Fig. 2.4** Orthogonal lattice structure in nature and architecture. **a** Glass sponge Aulocystis spec. **b** Experimental node-and-rod structure with rigid nodes by Frei Otto, 1962 (Adapted from Nachtigall and Kresling 1992a)

for further stabilization of the network. As soon as this process is complete, the formation of the next layer begins. In the ontogenesis of the sponge, one tubelike, closed, orthogonal lattice is layered on top of another; the outermost layers being the youngest.

Orthogonal lattices consisting primarily of flexibly connected members are of course not stable in themselves. Why would nature then work with such systems?

The architect Frei Otto designed similar orthogonal lattices (Fig. 2.4b). In his design, the nodal points could no longer be articulated and had to be formed as rigid nodes so that the system remained stable. The structure is used mostly as a load-bearing floor system, therefore for bearing loads in the horizontal direction, and as it is planar, it needs to be supported from below in small enough frequencies to avoid bulging.

In contrast to technical structures, material in biological structures is accumulated—and later hardened—in locations where bending stresses arise. These stresses are thus functionally used and simultaneously dissipated by the growth processes induced by them: The tensing movements by the membrane are co-responsible for the forming of pressure-resistant spines, from which the tension system is suspended. The linear growth of the spines increases in turn the tension in the membranes and is thereby co-responsible for their development.

> In organisms, which form a structural framework from precipitated, or in other words, initially viscous and then hardened materials, two-formation systems cooperate in feedback to one another.

The comparison of biology and technology yielded the following insight for this structural form: Nature clearly does not work according to the technological principle of pre-calculated, measured, and stably prefabricated structural elements. Because natural structures must be able to grow, they must work with "preformed deviation," meaning the admission of slight instabilities and resultant accidental variations. This insight signifies: Optimizations in a biological structure do not require reaching a form with an ambitious margin of safety. Rather, a structural form that is sensitive with respect to variations yet still precisely efficient is reached. Simultaneously, the partially self-evoked tensioning from the growth process is simultaneously used for the stimulation of this process, resulting in a network of building processes, function, and adaptations to specific structural loads.

Such self-organizing processes are understandably unable to be reenacted with large-scale building technology. They could however lead to, for example, experimental constructions for the fabrication of innovative materials. Engineers search for means to be able to consistently test the structural behavior of a building for potential failures or even to let the structure correct itself. Studies of micro-vibrations could in this instance, as they occur in the construction of the mentioned biological structures, provide worthwhile inspirations. It could also be that the inverted process is pursued; namely someone, who acquired knowledge about similar processes in technology, would a posteriori correctly describe or even correctly understand the natural processes. That would be "technical biology" par excellence.

Technical biology can also lead at the same time to insights that are and are not immediately usable in biomimetics (that does not devalue the technical–biological process by any means).

### 2.1.5 Panel Structures

Figure 2.5a shows the base forms of regular volumes, which one could construct from panels bound at their edges. They are three of the Platonic forms: tetrahedron, cube, and dodecahedron. The characteristic of a stable panel structure is accordingly the meeting of edges in a "Y" formation.

In 1984, the Danish engineer T. Wester found that there are strict, formal, and mechanical correlations between the network forming node-and-rod structures and panel structures. It is related to dual symmetries. Consequently, the computer programs developed for geodesic dome structures could be reformulated and utilized for panel structures as well.

One can construct a panel structure in such a manner that the panels are flexibly joined to one another at the edges. Shear forces (which try to shift the panels against one another) occur as a result. One can form the edges as linear joints (i.e., in the form of a piano hinge) or with dovetails: Such structures are also stable due to the Y configuration of the vertices of the panels—as long as no more than three panels meet at one vertex. If the joint lines of four panels intersect (then in the form of an "X"), one obtains a foldable structure as a rule.

In the first mentioned case, the complete structure finds itself in equilibrium when the sum of all occurring torques is equal to zero. A spatial structure can be composed from such panels; an example from T. Wester is shown in Fig. 2.5b, namely a building structure from load-bearing glass panels. It is almost certain that many biological structures, for example sea urchin shells, follow this structural principle (Fig. 2.5c). In these shells and in the shells of other organisms, the individual panels—with slightly dovetailed edges or seams—also meet in a Y form. One can actu-

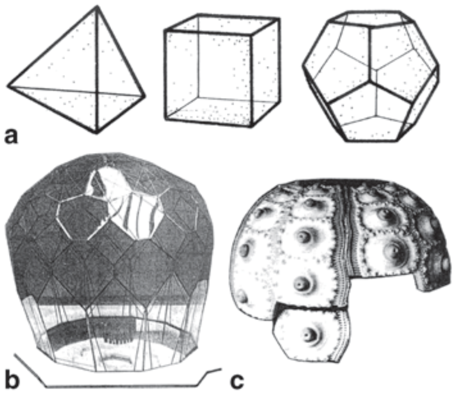


**Fig. 2.5** Panel structures in nature and architecture. **a** Platonic forms: maximum of three panels around one vertex. In stable panel structures the edges meet in the form of a "Y". **b** Project for a museum building by T. Wester and K. Hansen (1988). **c** Australian sea urchin *Phyllacanthus imperialis* from the collection of MNHN, Paris (Adapted from Nachtigall and Kresling 1992b)

ally remove the individual panels in older, completely dried-out specimens and insert them back in as well (“clipping together”), obtaining once again a stable shell. The sea urchin appears to integrate this ability as a growth principle. New growth marks always form along the edges of the panels and remain parallel to each other. “Neighboring panels grow so-to-speak at a right angle to their edges towards each other, so that theoretically only tangential shear forces can occur within” (Wester 1984).

Ute Philippi, a doctoral candidate under W.N.— in collaboration with the Institute for Structural Mechanics at the University of Stuttgart—concerned herself for some time with the finite element (FE) modeling of sea urchin shells within the frame of the SFB 230 (“Natural Structures”).

The studies yielded, among other findings, that the peculiar “apple-shaped” shell form is particularly well adapted to the tension forces caused by the tube feet and the undirected forces acting on the exterior. The shell presents no weak points. How is it formed then and how can it be statically functional even during its formation process?

To this question, the structural panel approach mentioned earlier can provide food for thought. However, it does not completely explain the essence of sea urchin shells; they possibly belong to technical hybrids, which one can understand only if one has understood “purely technical” entities and can combine two ideas: Perhaps the sea urchin shell behaves simultaneously like a panel structure (shear forces) and like a shell structure (bending-induced forces). Such structures are also not completely stable during growth but subjected to shear forces, which cause the panels shift slightly against each other, and “bending forces,” which are directed over the seams. These forces are however—as indicated by the glass sponges—functionally used: As panel structures, the sea urchins could use the anticipated shear forces on the interlocking edges of the panels expected in such a structural form for the accumulation of calcite crystals, as a stable shell structure it could use the deformations elicited by the shifting panels for its construction. In such a construction process, the biological shells could grow both longitudinally and latitudinally. Therefore, it could offer an interesting solution for a difficult technical problem, namely volume enlargement or diminishment, which is always linked with tension points in one direction or another along the surface. Combined linear and volume growth could be used for technological purposes, possibly for an assembly process.

The use of two seemingly contradictory structural principles by one biological entity suggests that this form does not occur in a static but in a dynamic equilibrium condition.

One could thus formulate the underlying model concept as follows:

> In certain biological building processes oscillations are used in order to reach an equilibrium state for any given case. The form that results from this dynamic process contains the characteristics of two antagonistic structural principles.

Both authors of the quoted article have noted in various discussions in the struggle to find the most appropriate approach that a completely typical characteristic has been addressed in the comparison of biology and technology.

They found it in its quintessence: “technologists and biologists should toss arguments and counter-arguments back and forth like ball. In a fair game it’s the playing itself that is most important—with the passing of the ball between biologists and technologists the alternating learning from one another should be an end in itself. In general, a result—like the final outcome of a game—from scientific discoveries and likewise from technological achievements is always only tentative: the game is never won, it is only postponed: the process is the goal."

### *2.1.6 Fold Structures*

As illustrated by the Japanese paper-folding technique ("origami"), one can fold paper into complex forms. The innovative Japanese physicist K. Miura technically implemented such fold structures, which are analogous to biological systems such as deciduous tree leaves, flower petals, folding insect wings, and possibly bee honeycombs or plant cells as well. This technique focuses on spaceship design and ultra lightweight design.

The previously described panel structures and Miura's fold structures allow comparisons. In both cases only tangential shear forces occur at the fold edges. A surface cannot be warped along a fold (or generally speaking, along the axis of a cylindrical or conical curve). This property functions for isotropic, thin-gauge materials, such as paper, due to their inelastic deformation behavior. The formal characteristic for a stable panel structure is, as stated, the arrangement of no more than three panels around one vertex. The panel edges functioning as linear joints therefore form a Y-fold structure. Because they should be light and rigid, they must be produced from the thinnest possible planar surfaces and be able to be folded together in space-saving manner (Fig. 2.7).

Structural applications require, for example, a large spanning width of the panels of a folding structure or additional folding elements, such as heat insulation. The construction of thicker fold elements is necessary for this purpose. These elements are limited in their ability to be folded together, but nonetheless retain the essential characteristic of fold structures, that is, the distribution of loads in third dimension. Owing to their complex geometries, folded structures have been hitherto difficult to produce. At the ETH Zürich and the EPFL Lausanne, Switzerland, research teams have occupied themselves with the construction of fold structures using wood (Fig. 2.6). As an outcome of the research results from the Lightweight Structures Institute Jena, Germany, a fold structure was developed by the architect team Steinmetzdemeyer/Pohl for the new convention center in Luxembourg that is supported by a lightweight and well-insulated wood construction and—as with the naturally multifunctioning capabilities of leaves for example—supplies solar energy and is partially transparent to allow light in. This structure is planned as a zero-emission convention center and as such can predominantly provide enough energy for itself (Fig. 2.8). At the University of Applied Sciences, HTW Saar, Germany, architects with G.P. are researching on comparable fold structures with the goal of achieving simple constructability using only woodshop and carpentry machinery.

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