

# Form-optimizing processes in biological structures – self-generating structures in nature based on pneumatics

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## Abstract

*“If architects designed a building like a body, it would have a system of bones and muscles and tendons and a brain that knows how to respond. If a building could change its posture, tighten its muscles and brace itself against the wind, its structural mass could literally be cut in half.”*

*Guy Nordenson, Ove Arup and Partners*

This case study is an investigation of self-generating forms in nature based on pneumatic structures and their use in architectural theory. It focuses on the concept of self organization as a defining principle in nature and, in particular, on the mathematical, geometrical and physical properties of bubble clusters and shows examples from nature, biology and engineering.

Part of the research resulted in a series of digital models and renderings of different bubble clusters and their polyhedral configuration. Advanced structural design methods are already using systems based upon self-generated models rooted in biological and genetic forms. Engineers are able to input a series of variables into a computer program which, in turn, derive a structure using a genetic algorithm resulting in the most efficient use of materials, etc. Numerous examples of such procedures already exist in nature today, in particular, in biology. Blueprints for these forms are stored in the genetic code of the DNA of all life forms. Until recent advances in computer technology, the ability to put such genetic algorithms to use has not been possible.

*Keywords: form-optimization, lightweight membrane-construction, radiolarian, genetic algorithm polyhedra.*



## 1 Introduction

The study of form-optimizing processes in biological structures has a long history starting with Frei Otto, Werner Nachtigall and followed by many researchers [2,3,4,10]. These researchers have outlined in a number of forms the mathematical relationships that control the overall geometry of polyhedral in biological structures [12]. The research centers on an investigation how optimizing processes in biological structures are possible starting points to generate optimized architectural forms and structures. For this particular study the bubble cluster based on the pneu was selected. The pneu is a system of construction comprising of a non-rigid envelope having a certain tensile strength, and an internal filling, which is in most cases pressurized. This system of construction can be translated into the architectural world in the form of pneumatic structures. This structural system, which can be found in many lightweight structures today, is based on the principles of those pneumatic structures found in nature.

## 2 Pneumatic structures in nature

One example of a pneumatic structure in nature is the soap bubble. In soap bubbles, growth is achieved through a system of division and inflation. This increased internal pressure encased in a reinforced membrane subject to tensile stress causes the bubble to grow in a process known as isomorphism or self-generation.

Free-floating bubbles collect and form dense clusters known as foam. If three bubbles are placed on a glass surface and a fourth is added, the fourth bubble will relocate to the top of the three bubbles to form the simplest three-dimensional cluster consisting of four bubbles. If further bubbles are added they will automatically form a foam structure. If the bubbles are of equal size the liquid edges of the foam are straight and of equal length and the angles of incidence at the nodal points are equal. The total structure forms a net of equal mesh size called the “basic net” (Fig. 2h).

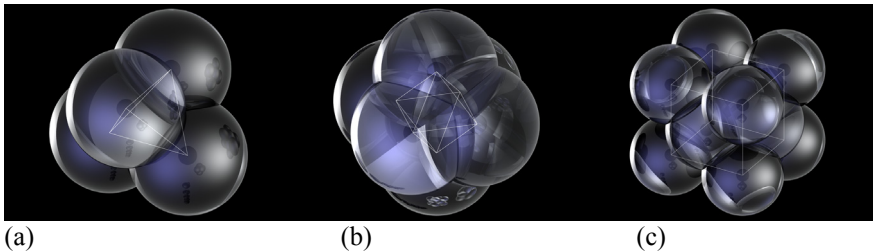


Figure 1: Rendered computer model: (a) tetrahedron bubble structure; (b) octahedron bubble structure; (c) cube bubble structure.

### 3 2-D bubble clusters

Net structures are formed through the solidification of a 2-D bubble cluster. Bubble clusters occur when bubbles are freely dispersed within a cell without touching each other. In the next phase, the bubbles are introduced to each other through points of contact and form patterns by agglomeration (Fig. 2a-2g). These patterns are based on geometric forms such as cubes, tetrahedrons and octahedron (Fig. 1). As solidification takes place, the membrane of the bubble dries out and the fiber net hardens (Fig. 2g). The bubble membrane then dissipates and the net structure is left (2h).

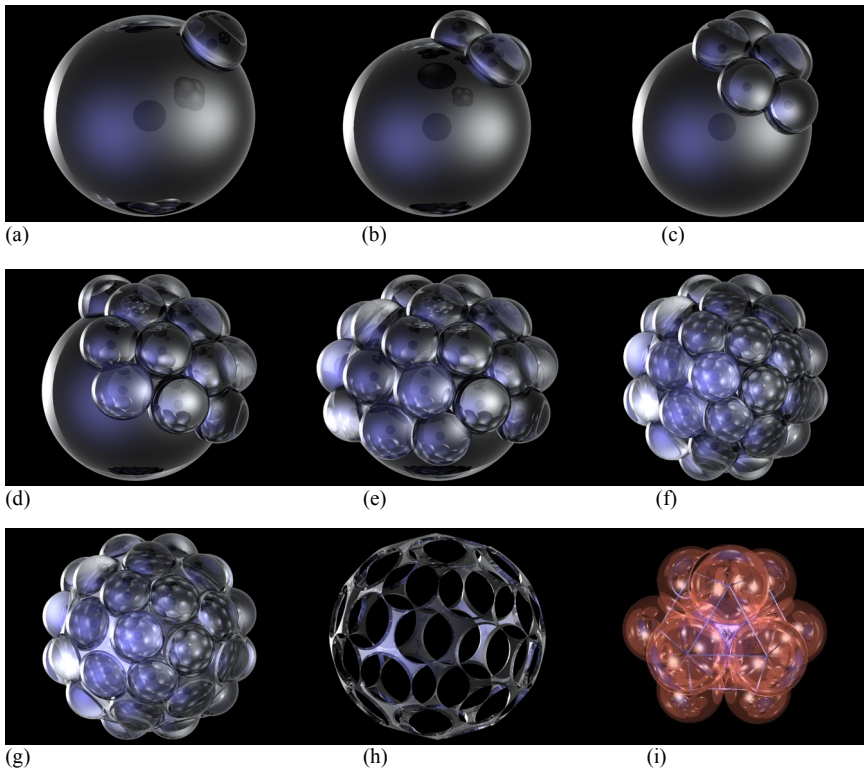


Figure 2: Computer model: (i) is the closest packing of spheres.

## 4 Mathematics/geometry

### 4.1 Closest packing

One of the fundamental geometric principles that drives the repetitive, self-generating forms in nature is the notion of *closest packing* [1] of spheres. It is



this which defines the curvature of an insect's compound eye or creates the formwork to mold a radiolarian's skeletal structure. As spheres are packed closely together, certain laws of physics cause geometric shapes to occur, such as hexagons. These polygons create repetitive surfaces among and around the spheres. In some cases, these surfaces find themselves useful for a number of functions, such as in an insect's eye. In other instances, these surfaces interlock together to create volumes, polygons create polyhedrons. These volumes may be used to serve a purpose.

Often times, it is not the surface or volume that is put to use in these systems. Quite likely, it is the edges along which these spheres meet that are of use to the organism. Once again, the radiolarian and diatom gather silicate deposits along the edges where the spheres meet around the outer surface. It is along these edges that a skeletal system is formed.

One of the greatest advantages to geometric systems based on the closest packing model is the great variety of configurations from which to choose. Repetitive, self-generating form can be derived in the shape of hexagons, pentagons, and even triangles (Fig. 1). These can be arranged independently or between various types [1]. After a particular form is created, it, too, can be arranged with other similar forms to create even more shapes or, in terms of architecture, spaces.

## 5 Structural optimization in engineering

### 5.1 Genetic algorithms

In engineering fields, accomplishing an objective with a minimum of effort, either in terms of material, time or other expense, is a basic activity (Fig. 7a). For this reason it is easy to understand the interest designers have in different optimization techniques. Mathematical, as well as, model based tools have traditionally been employed for such optimization. In recent times, mathematical methods executed on computers have become predominant. Unfortunately, computer derived solutions often obscure the range of possible solutions from the designer by only exhibiting a final, 'best' solution. Naturally, optimization methods can only respond to the objective parameters which are coded into the problem, and as a result, non-coded parameters, such as aesthetics, or context are left out of the optimization process, and ultimately left out of the final design solution.

Structural optimization in engineering takes natural constructions as an example (Fig. 3). Similar to nature itself, computer-generated genetic algorithms can be calculated using stated goals to achieve global optimization - the search strategy is, like in nature, goal-oriented. An evolutionary algorithm maintains a population of structures (usually randomly generated initially), that evolves according to rules of selection, recombination, mutation and survival, referred to as genetic operators. A shared 'environment' determines the fitness or performance of each individual in the population. The fittest individuals are more likely to be selected for reproduction (retention or duplication), while



recombination and mutation modifies those individuals, yielding potentially superior ones. Using algorithms, mechanical selection, mutation and recombination improves generationally with a fixed parameter size and quality.

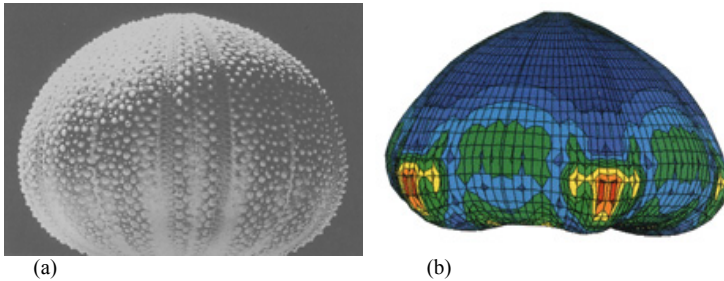


Figure 3: (a) Structure optimization in the shell structure of a sea urchin. (b) Finite element analysis of sea urchin shell, color coded stress analysis [15].

## 6 Computer-compressed evolution

### 6.1 Design space and finite elements

Computer-compressed evolution like the SKO method (Soft Kill Option) (Fig. 4) follows the same construction principle that nature employs to promote for example the shell growth of a sea urchin (Fig. 3) or the silica structure of radiolarian (Fig. 7d/8b). Building material can be removed wherever there are no stresses, but additional material must be used where the stresses are greater. This is the simple principle that evolution has used for millions of years to produce weight optimized ‘components’. Using computer programs based on computer-generated genetic algorithms like the SKO method, scientists are now able to simulate this evolution and compress it into a short time span. [9]

In order to simulate lightweight engineering strategy according to nature’s guidelines, scientists using the SKO method must first define a virtual design space, which represents the outermost parameters of the component being developed (Fig. 4). To subdivide this design space into many small individual parts, the finite elements, a grid is applied. If now a virtually external load applied, the computer calculates the resulting force exerted on every one of the finite elements. The FE model shows exactly where there is no load stress on a component and in turn shows where it is possible to make savings with regard to the materials used. On the other hand, for areas that bear heavy stress the simulation program indicates the need to reinforce the construction material. Like nature the computer repeats this ‘finite element cycle’ several times. As a result, they can refine a component repeatedly until the optimal form — one that evenly distributes the stresses within a component — is found.



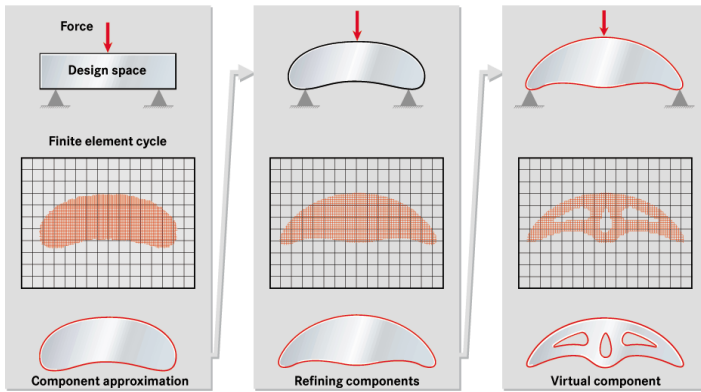


Figure 4: SKO method (Soft Kill Option). The DaimlerChrysler Research Center Ulm and Uni Karlsruhe, Prof. Claus Mattheck, in Germany developed the SKO method (Soft Kill Option) [9].

## 7 Biological models

### 7.1 Radiolarians and diatoms

A number of self-generated, biological models based on the bubble cluster theory exist. One of the best examples of this is the *Radiolarian*. Radiolarians are single-celled marine organisms. These microscopic creatures extract silica from their environment to create a skeleton. Highly articulated geometric patterns define the usually spherically shaped structures. The resulting form resembles that of a dome.

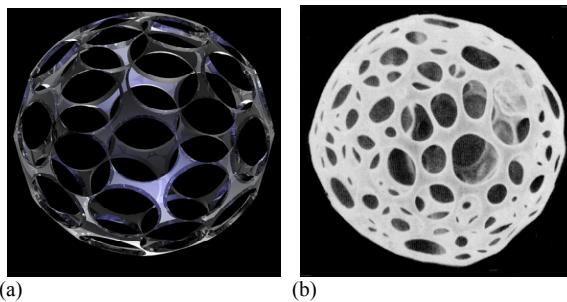


Figure 5: (a) Computer generated spherical cluster skeleton based on the bubble clusters theory (see Fig. 2a-2h) (b) fossilized skeleton Radiolarian [6].

The process carried out to produce such as resulting structure is a relatively simple one. A great number of vesicles, tiny sacs of fluid, are created. These bubbles are essentially tiny versions of the larger soon-to-be cell (Fig. 2c-2i, 3a).

They are the common modules for the cell. As the vesicles begin to pack closely together in a radiating pattern, the resulting form is a spherical mass, the cell. The unique geometry of the cell's surface, as produced by the closely packed bubbles, is the formwork for a skeleton [4].

Within the crevasses formed at the edges where the bubbles contact one another, silica particles settle and join together. The geometry created by the bubble connections allows the silica to form a series of interconnected members of similar size and shape. The result is a complex-looking skeletal structure made up of a great number of simple, relatively similar members.

To create such a seemingly complex system for so simple an organism, it is necessary to build upon highly efficient mathematic and geometric principles. These principles are embedded in the genetic code of the radiolarian, and similar life forms.

A number of diatoms share similar characteristics with their single-cell cousin, the radiolarian. Some of these include: radial form and a ridged skeletal structure. The skeletal structure of a diatom is not necessarily spherical, but it is radial. Tiny bubbles radiate in a closely packed form to create the cell shape. This bubble form is decrypted as a "foam-raft". Once this occurs, silicate deposits meet along the bubble edges to form the skeleton. This material forms what can be considered actually a "glass" skeleton.

Variations of diatoms are numerous. Not all diatoms are perfectly round in configuration. For instance, some are actually triangular in shape. These diatoms still adhere to the closest packing principles, just a different version than most. Other types of diatoms are oblong in shape. Instead of a repetition of similarly shaped spheres, or bubbles, these adaptations pack together larger, tubular forms to create their skeletons.

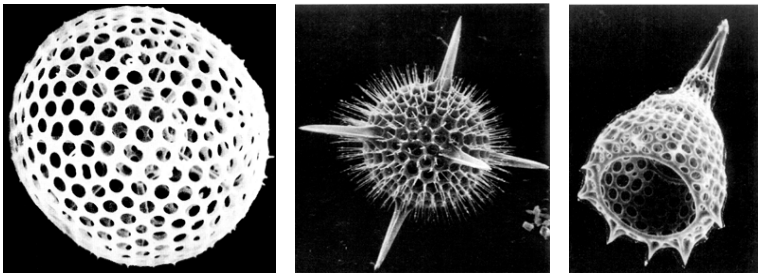


Figure 6: Radiolarian and fossilized skeleton [5,6].

Diatoms, and radiolarians alike, are chief examples of highly efficient structural systems with simple enough geometries for organisms with limited genetic information storage capabilities.

## 7.2 Fullerene

The smallest known and just recently discovered structures based on the principles of self generation, closest packing and polyhedral are the fullerenes.



Fullerenes (Fig 7) a class of cage-like carbon compounds composed of fused, pentagonal and/or hexagonal  $sp^2$  carbon rings were first discovered in 1985 when the soccer ball shaped  $C_{60}$  (Buckminsterfullerene) was synthesized. The novel phase of carbon was named after the engineer and architect Richard Buckminster Fuller (1895-1985) as the molecules share the architecture of his geodesic domes. Fullerenes are range in size from 20 to over 500 carbon atoms.

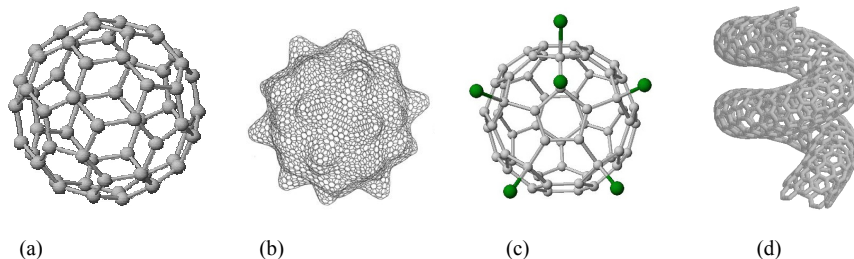


Figure 7: Different models of fullerenes. Fullerene Research Centre [14]. Left to right:  $C_{60}$ ,  $C_{60-}$ , Exohedral Fullerene Compounds  $C_{60}$ ,  $C_{16}$ , Nanotubes.

The carbon atoms in  $C_{60}$  are arranged in a geometric shape consisting of 12 pentagons and 20 hexagons. Other spherical fullerenes (collectively known as buckyballs) were subsequently synthesized with a different number of hexagonal faces. The smallest possible fullerene is the dodecahedral  $C_{20}$ , a shape consisting of 12 pentagonal faces and no hexagonal faces [7]. Larger fullerenes have been found to exist in nature [8]. Nanotubes, nanohorns and buckybowls are other examples of fullerenes [14].

## 8 Architectural applications

Commonsense nature - producing maximum effect with minimum resources.

### 8.1 Structural configurations

Just as volumetric and formal configurations are quite various, so, too, are the structural configurations of closest packed organizations. Structures with the qualities of domes are not the only forms that can be used and turned into a building. Variations in the manner in which the polygons go together can create long-spanning tubular structures and volumes.

The basic way to derive these structural schemes is to place relatively thin, load carrying members along the edges where the polygons meet. When configured correctly, these are the points at which forces naturally occur. Based upon the geometries of that form, it is likely that a highly efficient system is the result.

One of the greatest benefits of this type of structural design is the relatively small number of member sizes. When multiple polygon geometries are involved,





other members and connection types are necessary, but all can be accounted for in the initial design.

## 8.2 Fuller's geodesic patent

Applying the science of self-generation to architecture has yet to be fully realized. Attributes of biological examples, like the radiolarian, do currently exist in structures like Buckminster Fuller's *geodesic dome*. Fuller recognized the closest packing of spheres phenomena in nature and used it as a model for his dome based on those mathematical principles. One of the most revolutionary innovations Fuller developed with his geodesic system was the repeated use of highly efficient, similar members. This allowed for the self-generating/repeating method of construction already in use by nature.

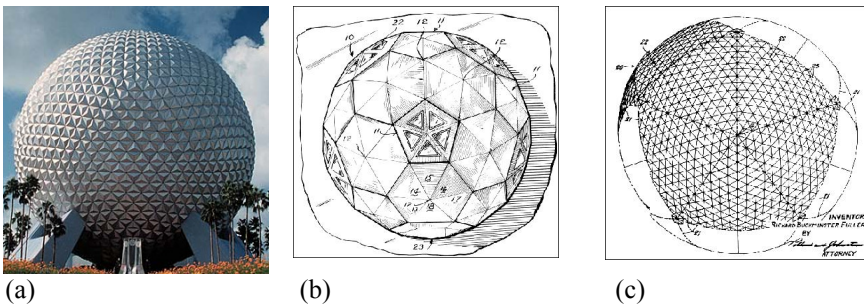


Figure 8: (a) Geodesic sphere (b and c) Fuller's geodesic patent drawing.

To take Fuller's discoveries one-step further using today's technology, it is possible to generate structural optimized structures in a computer by using for example the SKO method to create not just a representation of a biological form, but to reproduce the evolutionary steps taken to make a structural system most efficient.

## 8.3 Eden Project, Cornwall, GB, Nicholas Grimshaw architects

A recent example of polyhedral structures in architecture is the Eden project completed in 2001 by Nicholas Grimshaw. The Eden project is a botanical garden and education centre within a former china clay quarry. The construction of enormous greenhouses (biomes) created a sheltered micro-climate and enable large numbers of the world's tropical and Mediterranean species to be represented within the plantings. The building foundations follow the complex contours of the pit and support the lightweight tubular steel geodesic domes which are interlinked with arches. The largest of these domes is 100m across and 45m high internally.

The Lightweight ETFE foil pillows form the cladding system between the dome members with panels up to 11m diameter providing maximum light and



UV transmission. These hexagon shaped bubbles were used as they can settle perfectly on to any shaped surface.



Figure 9: *Eden Project, Cornwall, GB*, Nicholas Grimshaw Architects, Anthony Hunt Associates engineers, structure: MERO Membrane ETFE-Pillows diameter 9 m, Dimensions: 15 590 m<sup>2</sup>, 100 m x220 m height 55 ([www.anthonyhuntassociates.co.uk](http://www.anthonyhuntassociates.co.uk)).

The Biomes' steelwork is extremely light and is anchored into the foundations with 12-metre long steel ground anchors. The design comprised a two-layer steel curved space frame, the hex-tri-hex, with an outer layer of hexagons (the largest 11m across), plus the occasional pentagon, and an inner layer of hexagons and triangles (resembling huge stars) all bolted together like a giant Meccano kit. Each component was individually numbered, fitting into its own spot in the structure and nowhere else.

#### 8.4 National Swimming Centre Beijing Olympics 2008, Peking (CN), PTW, Sydney & C S C Eg Corporation, Peking & Ove Arup Pty Ltd., London

The winning project for the international design competition 'National Swimming Centre Beijing Olympics 2008' by the Australian architectural firm of PTW is another example for the efficient combination of polyhedral structures with ETFE cushions. The design, called 'Watercube' is a simple and concise square form that ultimately uses the water bubble theory, the natural formation of soap bubbles, to create the structure and building cladding.

The structure system, a space frame, is based on polyhedral cells in different dimensions, the most effective sub-division of three dimensional structures. It is also based on the way that structure in nature tiles spaces. The building's skin, made from ETFE, has been designed to react specifically to lighting and projection.

## 9 Intelligent structures and materials

### 9.1 Self-organization as the defining principle of nature

The load bearing structures in nature condense accordingly to the structural needs. This phenomenon can be seen for example in the human thighbone and the arrangement of the sponge-like bone substance. As a result of a functional and



highly ordered design countless irregular cavities are interspersed with small trabeculae. The fine trabeculae are spatially organized to exactly follow the force lines of the tensile and compressive stresses that occur within the bone. The same structural principle that a structure has to grow where structurally needed, can be seen in other structural forms like tree structures, shells, lattice shells and as shown before in radiolarian structures based on bubble clusters (Fig.2a-2g). Radiolarians condense the structure accordingly to the flow of forces, which it controls through the diameter of the individual bubble. Bubble clusters with a high amount of small diameter bubbles have a larger amount of membrane surface, which finally results in a denser skeleton structure. The hardened bubble cluster reflects the amount of stress within the whole structure.

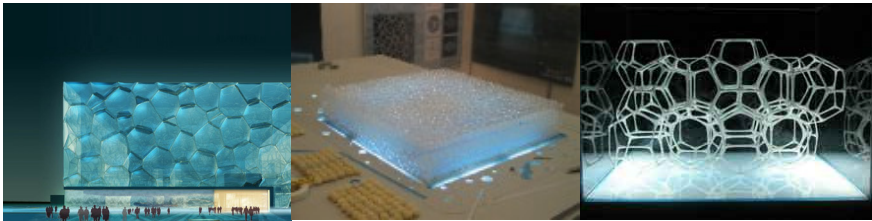


Figure 10: The members are fabricated from three plates with circular end plates. The nodes are simple steel fabrications with circular plates for the end plates on the members and corresponding holes to receive the bolts. These two elements are simply bolted together to form an assembly. The assemblies are bolted together to form the space frame (Ove Arup Pty Ltd).

Buckminster Fuller's and Nicholas Grimshaw's geodesic domes are based on repetitive polyhedrals. The dimensions of these polyhedrals do not take forces occurring in the individual members under consideration. The first built building based on a polyhedral space frame that takes the actual flow of forces into account will be the National Swimming Centre for the Beijing Olympics 2008, designed by PTW, State Construction Engineering Corporation, Peking & Ove Arup Pty Ltd. Like in radiolarian skeleton the structure condenses where the forces in the structure are increases.

Polyhedral structures based on the bubble principal are perfect study models for self-generating structures in nature because of there relatively simple physical and morphological principles and geometries. Self-organization is the defining principle of nature. It defines things as simple as a raindrop or as complex as living cell - simply a result of physical laws or directives that are implicit in the material itself. It is a process by which atoms, molecules, molecular structures and constructive elements create ordered and functional entities.

At its best, intelligent structures and materials will influence the entire philosophy of construction. Engineers will no longer ensure safety through quantity of material and cost. Simple structural analysis will no longer suffice; instead, self-organizing structures will define the new construction principles.



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