On Rules and Roots: The Organic Model in Design

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Abstract Digital tools and new technology are changing all aspects of today life, up to architecture and design concepts. They allow a new approach to the nature as a model, which is a concept that drives the theory of Architecture trough centuries. Then the affirmation of digital technologies is radically changing the application of organic models, which does not concern the shape any more, but just the morphing process. The aim of these notes is to stress significance, reasons and evolution of this reference that confirms the strong relationship between the theoretical heritage of architecture and its today developments, due to the application of digital technology to design, fabrication and construction. The making process find its theoretical validation in shape grammars and in traditional concepts of module, tessellation and pattern, which rules the design of decoration, surfaces and ordered conformations. Digital application of old basic design's confirms the value of this heritage as constant of architecture theory.

Keywords Pattern · Tessellation · Lattice · Symmetry and asymmetry · Organic models · Basic design · Design theory

1 Introduction

Contemporary architecture has always set the concept of order. It evokes the continuous stress between the tidy cosmos of creation and the chaos that preceded it, with surfaces, which suggest continuous transformations. Its shapes are inspired by the earliest studies in topology, whose spaces no longer obey Cartesian rigor, and imply a continuous formal evolution. The reference to the mathematics often suggested new ideas to architecture and still does, not only because of their

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applications in computer graphics but mostly because of the suggestion of innovative concepts, the same way that the "other" geometries that negated Euclidean geometry's postulates did. Walls and roofing bend, twist, merge in complex surfaces, without any apparent reference to their previous compositional rules, which were the goal of static, functional and esthetic needs, according to Vitruvio's triad *firmitas, utilitas, venustas.*

Computer-aided design is able to apply complex mathematics and architecture develops new shapes with bending surface—such as nurbs—and complex forms, using of the random repetition of simple algorithms, sometimes without the designer even being aware of the mathematics behind it, thanks to software that allows to model shapes directly. Thanks to a controlled randomness, the computer introduces chaotic elements into the architecture layout, imitating the contemporary world. In its articulated morphology it is difficult to recognize a classical concept of order, but a rule does exist and it is a code that manages the shape. Nevertheless, architecture still requires a balance between inside and outside forces its elements, therefore it cannot avoid the enforcement of rules that ensure harmony of shapes and strength. Design simply develops a different answer and then shows new forms, because of a different approach to models man always found in the organic reference of nature.

The design making process follows an organic-wise growing concept and the observation of nature offers a valid approach to design teaching. Drawing is the essential language of architecture. It expressed concepts through simple signs that are correlated to actual shapes of objects. A geometric thought ruled design and its representation. In the full digital age, the representation of virtual model is no longer the project media only: digital design is the goal of the development of a process that applies transformation rules to a ordered system. The design overlaps the making process through the same digital model. The last is sufficient in itself to the "making"; therefore digital fabrication eliminates the gap between the designer and the worker.

The scripting is the new drawing, because it manages shape grammars and objects morphology. This fact "brings back" to the old world of craft, when the drawing was not a mediated instrument of the project's language but it served directly the construction.

The man's inspiration from natural forms is a recurring citation in treatises and in historical literature, as well as in recent theories, which incorporate many concepts of basic design. The statement that nature is the first model of design has guided the theory of Architecture for centuries, from Semper and on. Along times, it became a myth that showed different evidence. Natural forms appeared first in ornaments and decoration, then they inspired building structures, later the organic model becomes a cyclic recurrence in Architecture design. What changes is only "how" man apply nature's models to its creations. In facts the late development of digital technologies allows a "leap" in the organic reference of design, which does not refers to the form as a static element but to the growth as a dynamic process of transformation. This improves the evidence of organic forms in design objects and therefore it increases the importance in design learning.

This paper resumes a wider research on the role of organic models in design teaching. In the starting phase, the aim was to retrace the significance of organic models in Architecture as a teaching tool in drawing classes. Before digital design became a reality, the goal was simply to understand the rules of form and growth to master shape grammar in design. Today it is the way to master the scripting of generative application as a rational process, avoiding that the organic reference became a bare formalism. That previous didactic experience that acquires new significance with the development of digital technologies, to introduce the application of design rules as a dynamic process, thanks to generative software. It becomes basic information for a competent application to digital design. It states the historical roots of digital design and demonstrates the timeless importance of few basic rules of shape grammars (Fig. 1).

The first research aimed to explain why and how nature became the best design model. This paper focuses on the transformation of the reference to natural models along centuries, depending on development of scientific knowledge. The first theoretical knowledge came just from the ancient overview of tidy Geometry in nature,

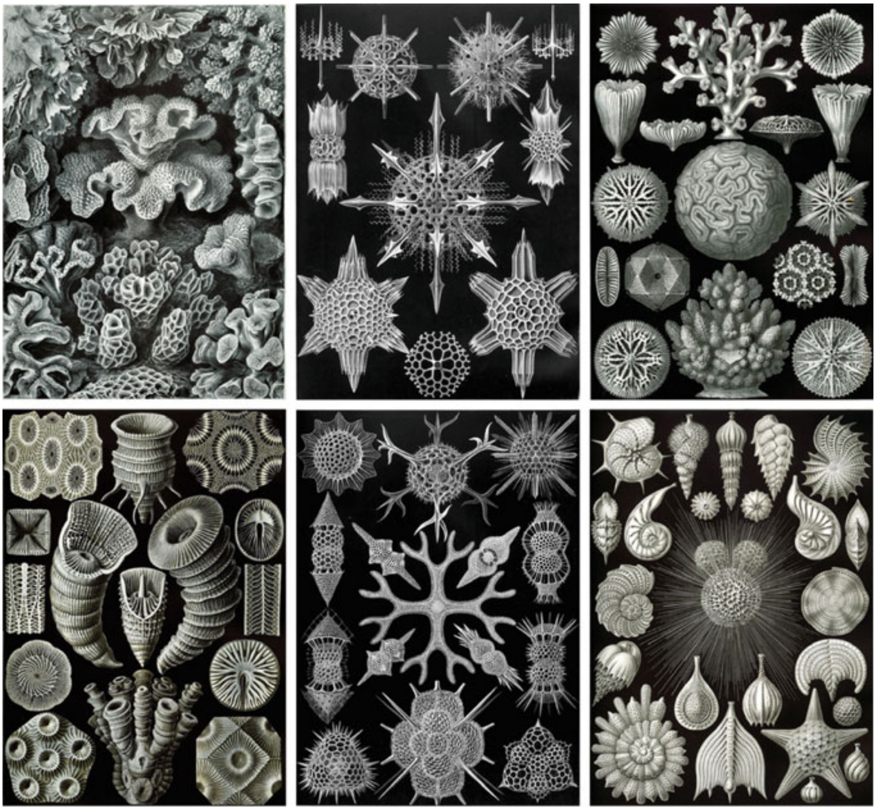

Fig. 1 Ernst Heckel (1904) *Kunstformen der Natur,* tables 1, 9, 29, 41, 69, 91

founding the reasons of Geometry as a creation rule, explaining growth process laws in living beings and therefore their imitation in architecture, eventually the evolution of the organic approaches in design, which started from the imitation of form to reach the imitation of life. The paper pursuit different aims:

- to explain the origin, the evolution of nature's myth;
- to understand the scientific reason of nature's configurations;
- to show the evidence of basic shapes and patterns in the organic models and their imitation in design;
- to help the management of shapes as a morphology process.

2 Nature as a Design Model

The perception of beauty was (and perhaps still is) related to a net order that rules the repetition of basic self-connected elements in different conformations. As a matter of fact, nature experimented with several variations on the same theme, combining simplicity and complexity [1].

The eurythmic conformations of nature's creations inspired mankind since antiquity. Men admired and copied their mathematical regularity in the design of ornaments. Regular patterns are evident in the shape of (lower) organisms, such as shells and flowers, becoming the first source of imitation. It was found in the chemical structure of the matter, as well.

The theory of Architecture used the reference to nature as a organic rule in the concept of complex artefacts, because it combines functionality, durability and aesthetic value in a sole expression. The imitation appears in structural design with aesthetic and formal values. The classical theory of the Order is exemplary but any human inventions develop from, or refer to, nature's example.

The imitation is linked to knowledge, because it is the first, elementary way of learning; in facts the man searched and found the inspiration to solve any constructive problem in the nature, which offers a great variety of formal solutions. Its regular configurations became a hard reference both as aesthetic and as structural model. They inspired the general layout too. Furthermore they invited to the search of an absolute law of harmony that pushed to the empirical birth of Science. So the wonder for nature characterized the birth of Western thought. It taught Architecture and led to knowledge, documenting how the man linked the formal symmetry of the natural balance, to the divine perfection.

Classical philosophers sought the answer to the origin of things and life in the observation of the physical world, trying to explain the law that rules the order of concatenated conformations. Heraclitus said that to achieve the wisdom you need to understand the principle that is at the origin of things, namely the $\lambda o \gamma o \sigma$ = *logos* [2].

This concept goes through Greek philosophy, for which things are made of numbers and geometry, with the meaning of word and speech, but also of measure.

The concept of proportion, apparently based only on aesthetic principles, before Galileo's innovations has been the first reference in structural design. The statement of a link between structures stability and visual harmony stresses the evidence of the Vitruvian triad [3].

Several scholars of Modern Age searched for a scientific explication of regular form in organic models as an answer to design questions. Kepler and Cassini studied the regular forms of bees' structures [4]. Galileo, who is the father of modern science, said that the book of nature is written in the characters of geometry. Descartes reconciled numbers and shapes and Kant stated that just nature can introduce Mathematics into natural philosophy. Later Einstein himself expressed the same concept, translating the link between energy and matter in mathematical terms.

Even without any final answer to the secrets of the universe, man found the solution to design and aesthetic problems in the observation of creation. If the Vitruvius statement "*deus architectus mundi, architectus secundus deus*" is true, in order to imitate God, man should really just imitate nature.

To imitate does not mean *to copy*. It means to reinvent, namely to understand and transform. Thus the imitation requires a deep knowledge, which follows a careful observation. Leonardo's work is a good example. The imitation of nature in design emphasizes the significance of observation and the role of drawing in the understanding of formal laws, which requires the management of shape grammars trough geometrical rules. Kepler's statement that Geometry is an absolute concept, it requires knowledge of formal phenomena of nature, which were the first basic assumptions of empiricism [5] and then of the experimental science (Fig. 2).

The acknowledgement of mathematical rules in nature is the focus of design imitation. It supports and justifies the application to design.

In nature's realms there are all forms of geometry, from simplest, such as regular polygons in the circle, to the more complex ones such as logarithmic spirals and minimal surfaces, as well as a wide variety of patterns and lattices with complex symmetric aggregations until the articulated forms of higher organisms. All these

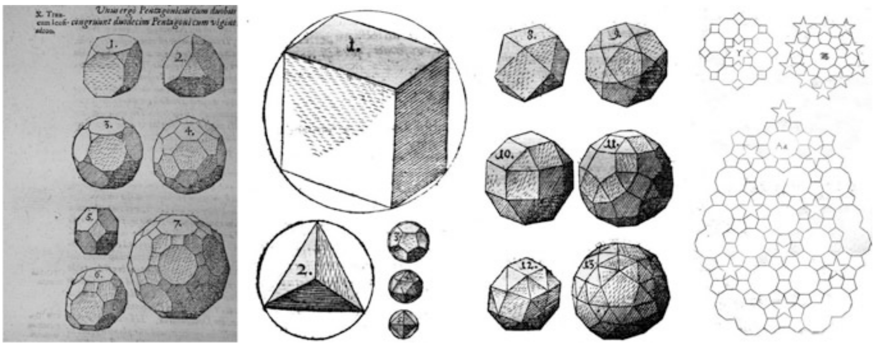

Fig. 2 Kepler's study of regular lattices in regular and semiregular polyhedron and complex plane tessellations

forms are never casual [6]. The geometric structure of molecules builds spatial lattices that are similar to those of Fuller's reticular structures. When it gets larger it turns regular forms into crystals, such as snow crystal.

A regular pattern affects the morphology of living organisms, for which the shape is an element of recognition and survival, and constitutes the final goal of the process that is implicit in life. This fact, which is evident in the net geometry of lower organisms, recalls the concept of Alberti's concinnitas. The last is the fundamental nature's rules that lay in perfection of Geometry.

In complex organisms the form is ruled by the gravity and the growth is regular but not homogeneous. It develops applying logarithmic relationships, with solutions of increasing complexity up to the mechanical efficiency of the vertebrates' skeleton.

3 The Nature's Law: Symmetry and Asymmetries

Alike builders, the nature must operate with materials of predetermined magnitude. The form is defined by the absolute or relative size properties in any directions and it is subject to the chemical and physical laws of matter. D'Arcy Thompson explains that organic forms are the effect of the physical system, which obey to pressure balance in cells and to mechanical forces in larger structures. Then the force of gravity controls the shape of higher organisms, while the surface tension determines the cells' shape that tends to the sphere and related forms. The pure, natural form gains the lowest surface according to the internal volume. External forces produce transformations in the shape to balance the system according to the criterion of maximum efficiency that characterizes the nature (Fig. 3).

Cells have a similar behaviour with the soap bubbles and they reproduce the Plateau's surfaces, whose symmetries appear in configurations of several protozoa [7]. *Radiolaria*, which are single-celled organisms with a silicate skeleton, show the full set of regular polyhedron. *Foraminifera* have a wide variety of allied forms,

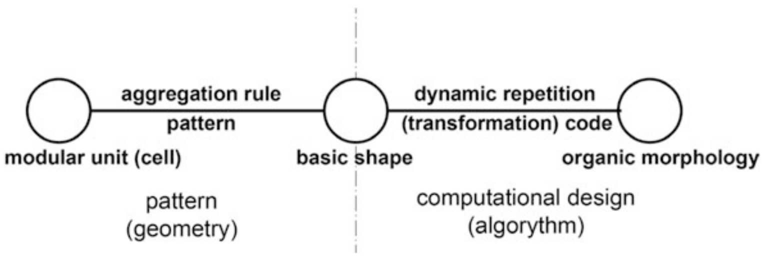

Fig. 3 Organic model and computational design: the development of design from "shape composition" to "form generation"

which document a continuous transformation between related structures that is not due to evolution [8].

The body is more than the simple sum of its members: it is the $\tau\varepsilon\lambda o\sigma$ = *telos*, which is the final goal of the living process of generation and growth that shapes its own form. Natural structures develop according to their final purpose and their body must be compatible with life, which relates to reproduction that is the basis of life. The primary element of biology is the cell, a living aggregation of organic molecules that are in turn compounds of chemical elements. The morphology of living organisms expresses the maximum efficiency of the biological process according to environmental conditions and the exigencies of cells' reproduction in the continuity of life. The form of organisms is the result of their growth from a single beginning cell that divides itself according to plans articulated in an increasingly complexity.

The growth is typical of life, but it is not its prerogative because it appears in crystals too. The transition from inanimate world to life is a unaccounted issue, but the origin of life seems to be due to a formal fact: the symmetry breaking. In fact symmetry is the main factor of stability that means absence of movement. On the contrary the asymmetry's loss of balance involves the movement and then a change. Life is a continuous changing.

Indeed the production of exclusively asymmetric compounds is a prerogative of life that manifests itself in ordered organisms, in which the symmetry shapes the general layout and cells multiplication [9]. The last one allows the genetic heritage with the duplication by cells' symmetrical division. The asymmetry of forces determines lines of weakest resistance along which the growth is greater. D'Arcy W. Thompson explains the morphological variety by obstacles to the action of growth, which by nature tend to be uniform and symmetrical. He demonstrates that the growth process exhibit asymmetries in the balance of internal and external forces, which determines lines of weaker resistance that are critical in the diversification of forms. The balance of forces alters the speed of growth of different parts of the same body. In the small dimension of cells they are subject to the balance between internal and external pressure, then to the law of the surface tension on the cell's membrane; in the great dimension of vertebrates they obey to gravity and to mechanic's laws.

Sometimes the growth maintains the beginning form, such as in snails. More often asymmetries and alterations of the growth speed produce variations that lead to the diversification of final structures.

The morphologists adopt deformations of a Cartesian grid to describe the transformation among similar individuals. Those homological grids 'measure' the differences between two corresponding points in different species. Variants and invariants among species can be explained with diagrams that show formal homologies among individuals. Sets of key points that are arranged in lines of variable bending, correspond to these topological transformations [10].

4 The Organic Reference in Design

Arts and Design applied the reference to nature's models in different ways. Since antiquity man was fascinated by the beauty of the natural world, regular conformations of crystals, simplest living creatures, up to the Renaissance, when the human body was the expression of natural perfection. The first approach was the primitive imitation in the pattern of ornaments and decoration, due to the admiration of the beauty of natural harmony of regular conformation in rocks, plants and animals. Because of the formal identity of fundamental entities a close relationship links geometry and architecture. It is evident in the articulation of building, in which different applications of mathematical models resolve problems of both statics and aesthetics.

Later architects found in nature the solution to specific problems.

The architectural Orders are a fundamental example, as well as the most famous, but they are just one in between many. Indeed nature offers a great quantity of references to structural, formal and aesthetic problems. The perfect layout of many natural conformations led to the obsessive search for a rule of beauty based on geometry, meaning number and shape. Along centuries, the imitation of nature's objects is not a trivial game without any rational reason, as it seems, but the repetitive reference to nature's perfection expresses a rule for aesthetic equilibrium. Therefore it became the best design model, and it still is, because of reasons that natural sciences may explain (Fig. 4).

Since the principal motive for these similarities between structures depends on the force of gravity—which subjects all bodies both natural and built to the same laws of equilibrium—it is not surprising to find similar static schemes verified by analogous mathematical models. The model of the structural system can be as static (shells and ribs) as it is mechanical (the skeletons of vertebrates) and sometimes the natural architecture is much more complex than the manmade architecture, since buildings require neither movement, nor velocity.

Architecture applied the model of skeletons to structures, imitating nature's balance in the proportioned relationship of building elements. Later it was the connection of parts in machines. Finally the imitation is fulfilled in the process of growth, which is the expression of life. In its digital procedures, the responsive Design copies vital process of life. The golden ratio expressed a symbolic reference to natural growth, the procedural design goes further and it copies it, shaping artificial life.

Observation demonstrates that the relationship that exists between natural and artificial architectures, in the common composition of parts according to rules governed by geometry and/or the growth of forms, underlines the concrete nature of the classic myth of the imitation of nature. Because of the various symmetries that exist in natural forms, the effective foundation of this presupposition is indeed geometry, capable of conferring harmony and equilibrium. It therefore becomes an important element of design and construction.

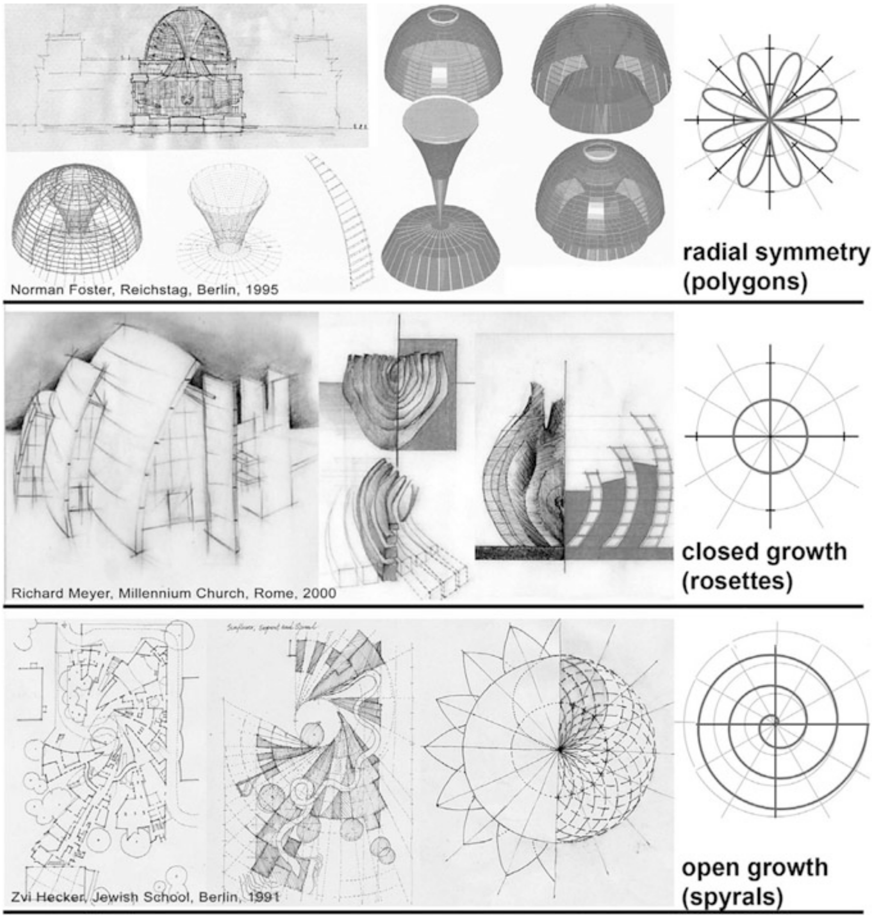

Fig. 4 Central pattern in architecture's forms with organic reference (student drawings). Circular patterns generate closed growth by increasing modules. Continuous growth becomes possible with spirals, which combine rotation and translation around a center

Good examples are M.C. Escher's and B. Fuller's work. The first "built the infinite" by the reiterate reproduction of cyclical divisions of the plan, which he applied eventually to the surface of the sphere using symmetry rules of five regular Plato's solids. His starting point was the cyclical tessellation of arabesque decoration, which recalls principles already defined in the late-nineteenth-century by ornament grammars. Those were also applied to wallpapers design. Escher extends the model to the pure concepts of surface and space, adapting plane patterns to the spherical continuous surface (Fig. 5).

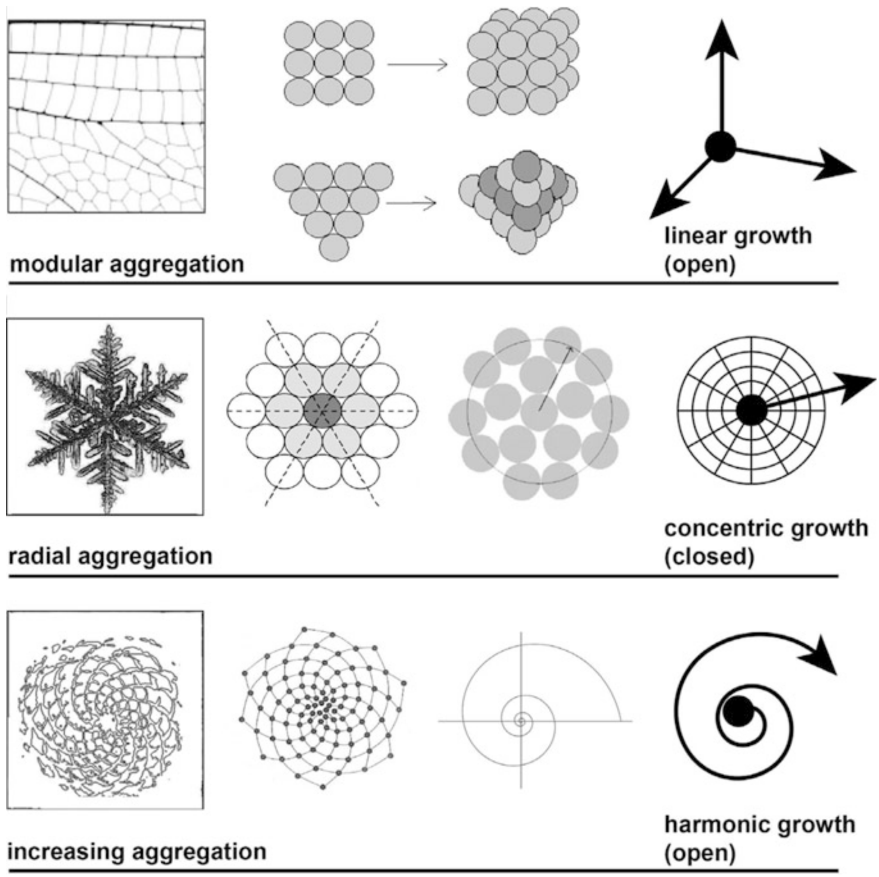

Fig. 5 Basic patterns of organic models. Patterns' structure stresses the difference between linear and radial aggregation of regular (uniform) cells: the first is open while the other is closed. Radial growth develops requires an increasing cells' number and produces net geometry only with hexagonal layout, otherwise it leads to aperiodical tessellations. (Penrose) Only logarithmic spirals allows regular (harmonic) growth

Escher's graphical inventions recall the works of Buckminster Fuller, who studied the spatial symmetries of the regular polyhedrons in order to solve structural problems. He applied regular pattern and lattices to the design of light structures, applying a mathematical program, deriving from the geodetic divisions of the sphere and/or the multiple symmetries of protozoa.

Effectively, mathematical models were developed to simulate reality by means of numbers, but geometry, which refers to form, is an concrete element of reality: everyone knows the logarithmic spiral of the Nautilus shell, the regularity of starfish, the perfection of the egg, and so on, but going beyond this, in protozoa are found living beings with the shape of all of the surfaces of Plateau, while radiolarian skeletons exhibit the forms of all five of the Platonic solids. It seems almost as though nature wanted to play with geometry.

Lars Spuybroek stated that computers have "*outgrown their servile function in the digital drawing room, where the real design was still done far away from the machines, sketched by hand, guided by genius*" [11].

The new computers' "cultural stage" gives new sap to the organic model in design, because they are able to go over the imitation of forms and structures. Computers master the process that lay behind the shape generation, such as the growth of living organisms or their adaptation to environment constrains. The imitation refers to life and its continuous transformation, not to the appearance of static forms. In nature "*all changes are small changes. Though a transformation can have a large effect, it is always a relatively small step, and the newness of the new can never be appreciated right away*" [12].

Any transformation applies the language of patterning, which bases on the four simple principles of symmetry. It can reach a higher level of complexity since bodies have internal and external transformation that interact with effects like merging, hooking, crossing, sliding, opening, nesting… The great variety of configurations in nature can be correlated to relatively few formal models based on different diagrams and symmetries, which make up the geometric basis of architectonic imitation. Both plane and spatial figures are always organised according to a simple diagram that can be traced back to three fundamental archetypes (Fig. 6):

- Modular aggregation according to a regular grid;
- Radial division of a circular unit in polygons;
- Linear continuity of spirals as regular growth of forms.

These models exhibit different kinds of symmetry and logic in particular growth patterns, and each of them has specific geometrical rules. Modular aggregation permits growth that is discontinuous and asymmetrical, according to the direction and the number of grid lines; it recalls histological tissue and can cover the plane and fill space, as well as expand linearly.

The symmetries according to which the base module is reproduced are four (translation, reflection, rotation and rototranslation). They combine with each other in very complicated ways, but they are always repetitive. The module is predetermined in relation to the fundamental grid diagram, but does not preclude a great variety of solutions (Fig. 7).

Growth is conditioned by the module, and this modifies complex form of the whole, which is indeterminate and thus permits the greatest degree of liberty. We can observe these models in the drawings of surfaces, in relationship to ornament and wall structure, and in the modular aggregation of spaces in plan as well as in spatial composition. We find them in the shapes of surfaces, in the structural mechanics of constructions, and again as an ambiguous game between the drawing of the surface and the representation of space. Radial division exhibits a closed form and a repetitive symmetry with respect to the centre, which often has mirror symmetry, but not necessarily the same number of axes. Growth takes place only in an outward direction, thus it is discontinuous and remains concentric so that the

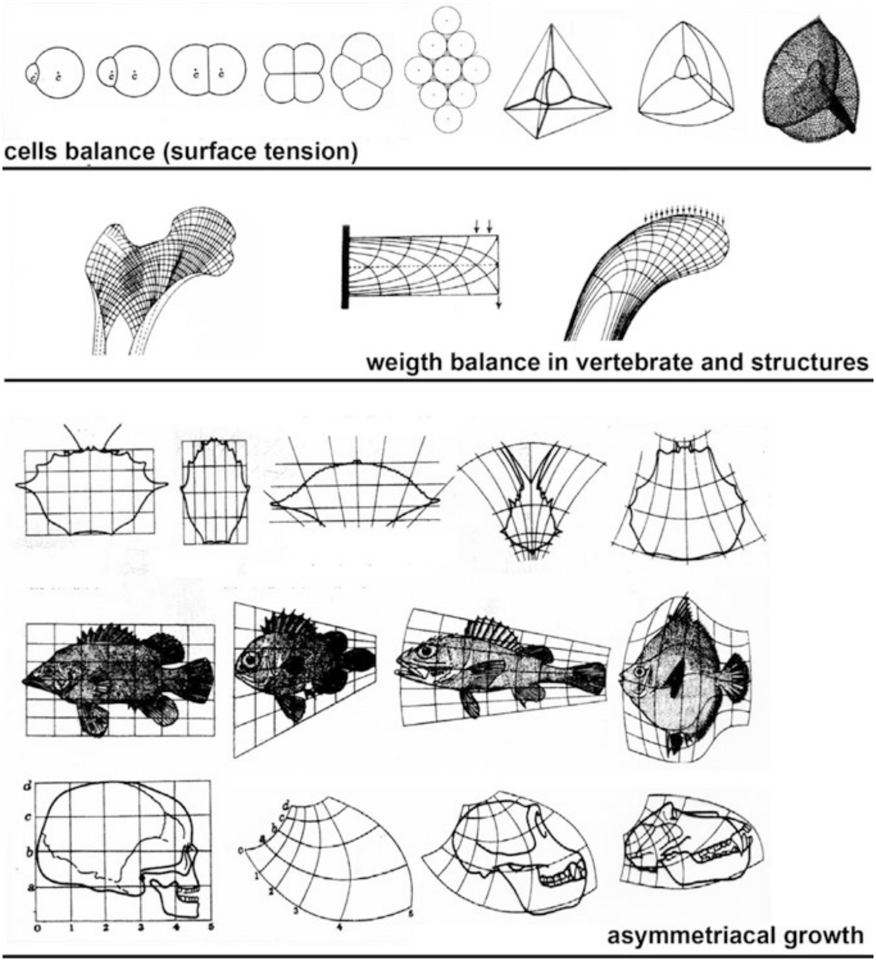

Fig. 6 Shapes and forces. Nature's conformations show as the (regular) shape follows the balance of forces: pressure on cells surface (surface tension), weight and gravity in vertebrates and structures, differential growing in biological variety (D'Arcy W. Thompson)

form is predetermined. This model can have a radial grid or can be aggregated in relationship to other grids. The extensions in space of this model are identified with rotated closed solids, such as domes.

Spirals derive from unidirectional linear growth that can be either planar or spatial, but which is usually refers to a continuity that tends to the infinite and to a particular rotational symmetry, which in logarithmic curves does not alter the proportions of the form. Thus growth is not discontinuous, and the form remains open.

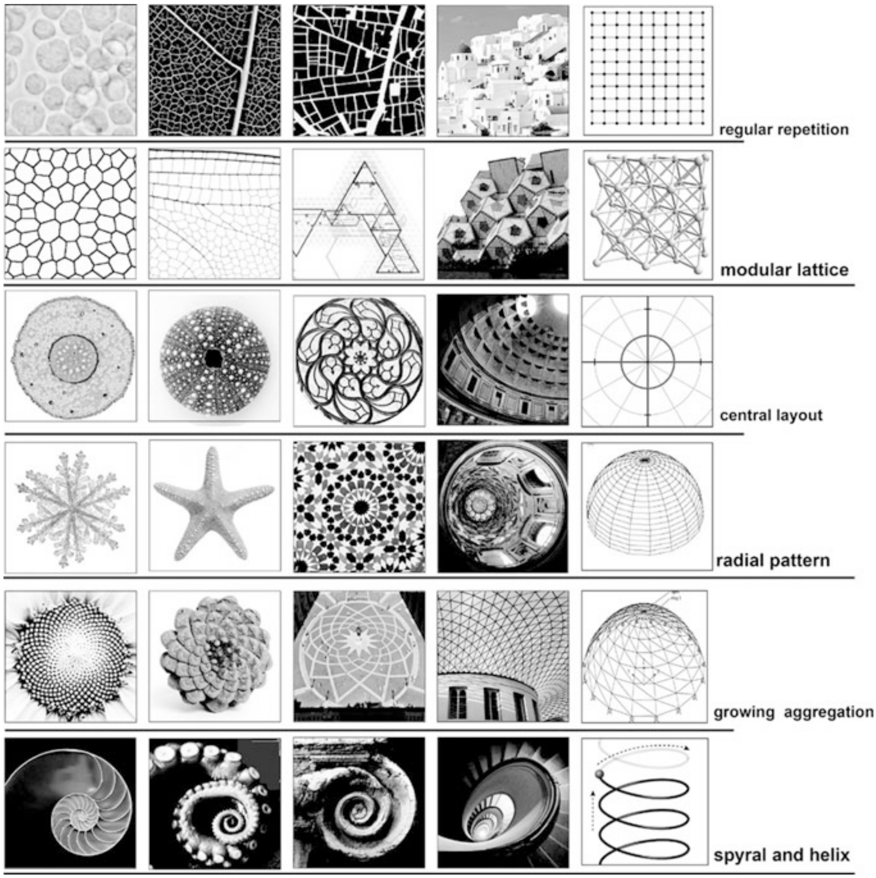

Fig. 7 Natural models and Geometry's rules. Basic conformations depend on cells and molecules aggregation in tissues and crystals, following basic patterns that develop different aggregation and growth possibilities. Design solutions refer to and interpretate organic forms in ornament, shape and layout

As a consequence of these conditions, man seems to have been particularly inspired by spirals since antiquity: spirals are used as special symbols of life and are manifest in art in different ways, while in architecture they become actual architectural elements.

Their spatial conformation generates complex surfaces that derive, however, from the regular motion of simple forms. Thus, since they are based on geometric rules, it becomes easy to draw, understand and construct the form.

These three models can be combined with each other in infinite combinations, each of which can be in its turn varied while maintaining homologous characteristics. These geometrical schemes satisfy various requisites of construction, suggesting solutions both formal and structural, with numerous examples found at all scales in architecture, from urban and territorial planning to ornament and surface decoration. We all know the significance that the concept of the module has in architecture and its importance in measuring, which is precisely the relationship between unit and quantity. Since this concept is directly connected to the use of modular grids that govern composition and proportion, it can be said that the design project makes reference to the concept of measure, and that this takes place through geometry.

The module is the basis of architectural order, which is the first principle of structures, organised according to spatial grids with orthogonal directions. In architecture cubic and pyramidal grids are common; in the regular organisation of the plane as well as the articulation of surface there are many possible solutions. In spite of its being a closed form, solutions based on the radial scheme are numerous and diverse; in drawings of plane configurations, such as those of rose windows or pavement designs, the number of the divisions and concentric elements change. This plane scheme is often used in urban design and in the realisation of buildings with a centralised and hierarchical spatial layout, in which the formal articulation is reflected in adjunct minor spaces. In spatial forms this scheme generates domes that can be composed of surfaces conceived according to different design solutions, in relationship to the structural choices for the building: continuous shells, ribs or geodesic grids as in the work of Buckminster Fuller.

5 Conclusion: Number and Shape—Drawing Rules and Design Codes

A regular lattice rules the aggregation of atoms in molecules and then in of more complex structures in a repetitive symmetry that characterizes the balanced harmony of natural forms. The ordered beauty of geometrical configurations of nature that caused wonder and admiration offered the main model to Man's creativity and first inspired decoration and artificial building. These ancestral models are attributable to the divisions of the unit in regular polygons that are inscribed in circles, to the continuous growth of the spiral or in the additions of gnomons and to the juxtaposition of repetitive modular elements in lattices. The basic rules of form are the same simplest operations of arithmetic and geometry: *division*, *multiplication* and *addition*. In the classical world the formal beauty was linked to a recognizable law that order the multiplicity in the unity: *symmetry*, *proportion* and *direction* resume rules that generate the shape. Together they express the *eurythmy*, which Gottfried Semper defines as a "*concatenated sequence of spatial ranges, similarly shaped*" [12].

Later the imitation recalled the relationships among elements in a closed system, just as Buckminster Fuller and Frei Otto did. Contemporary designers still explicitly refer to nature and its transforming processes, according to Lars Spuybroek's statement. The procedural design by generative software allows the digital imitation of organic models is not only a formal reference such as in its historical roots. It just pursues the dynamic transformation of shapes in living process. Generation of shape starts from a beginning tile and a developing concept. The form comes from the repetition of reiterate algorithms that change the shape adding new elements in the tessellation, turning the design into a process of biological growth. The configuration is the goal of a dynamic system that is regulated by predetermined codes, which are able to adapt themselves to boundary conditions, interacting with the surrounding environment. Similar shapes result from the management of a small number of formal parameters.

The dynamic model provides a even complex organization in which the rules of design meet to the homeomorphisms of the topological geometry.

Symmetry implies stability and balance; however it contrasts with the tension of growth and changing of living organisms that appears in the asymmetry of topological transformation. The imitation of Nature accomplishes in the continuous growth of generative design.

6 Notes

1. Ernst Haeckel, 1868.
2. B. Russel, 1959.
3. Plato, Fedon.
4. D'Arcy W. Thompson, pp. 126–129 (Italian transl.).
5. Plateau ha demonstrated that exist only 6 minimal surfaces that have 1 symmetry axe: sphere, plane, cylinder, catenoid, nodoid and onduloid. D'Arcy W. Thompson, 1917.
6. Keplero, Harmonices Mundi, 1619.
7. Plateau solved the Lagrange's problem (minimal surface depending on perimeter or volume) with sheets of soap water. In protozoa exist the 6 Plateau's surfaces. See D'Arcy W. Thompson, cit., cap. 3.
8. D'Arcy W. Thompson, cit., cap. 5.
9. Pasteur noted that the asymmetric structure is one of the deeper aspects of the difference between vital phenomena and not in life: "*this is perhaps the only line of demarcation that marks the difference between the chemistry of living matter and of matter that is not alive*". See D'Arcy W. Thompson, who stresses that in Nature the life develops often from a simple tube.
10. The Osaka Group states that the Nature be inclined to predetermined patterns. See J. Fodor, M. Piattelli-Palmarini, 2011.
11. L. Spuybroek (2004), p. 9.
12. L. Spuybroek (2004), p. 4.
13. Gottfried Semper, 1860. See the introduction.

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