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Natural Architecture and Constructed Forms: Structure and Surfaces from Idea to Drawing

This work grew out of didactic experience in architecture classes at the universities of Florence and Parma. The comprehension of geometric schemes in regular organic objects formed the basis of teaching drawing and scientific representation, such as formal architectural synthesis. This exercise may offer also a valid starting point to help students approach mathematics, and help them to imagine and plan the increasingly complex surfaces of late contemporary architecture.

Drawing and architecture

Just as mathematics speaks through numbers, drawing is the compositional and essential language of architecture. This language is used to express concepts through simple planar or spatial entities, correlated to forms generated by geometric thought.

Because of this formal identity of fundamental entities a close relationship has developed between geometry and architecture. This relationship is evident in the articulation of built form, in which diverse applications of mathematical models are found, used to resolve problems of both statics and aesthetics.

The connection is particularly clear in drawing, in which references to geometry are used to explain and describe complex forms. In fact, drawing and geometry link architecture to mathematics and express the same concepts, since they allow the form to be seen in reference to the elements of point, lines and planes.

Fig. 1-3. Villard de Honnercourt: geometric grids in drawing construction of natural forms

This fact is evident in the teaching of architecture, where since the age of Vitruvius the two disciplines have shared a pre-eminent role without necessitating any particular modification of language – of common usage – between mathematics, or geometry, and design and architecture.

The *Sketchbook* of Villard de Honnecourt¹ is significant in the use made of drawing during the Medieval, of outlines and simple geometric forms. Various Gothic designs confirm the role of geometry in governing the statics of the structure through the use of the simplest plane forms: the square and triangle, used respectively in the design of plan and elevation (figs. 1, 2, 3).

Thus geometry offers a means of learning drawing and understanding meaning, since both drawing and meaning appertain to architecture.

Since we draw things by means of their apparent outlines and the discontinuous lines between surfaces, it is important to study the nature of their intersections. The principle problem resides in the difficulty of verifying the spatial characteristics of the most complex forms, such as are found in architecture: a meaningful example is the intersection of curved surfaces in vaults and domes.

The scientific solution of representation derives from the reduction of three-dimensional forms to the plane by means of projective and descriptive geometry,² but in actual fact architects resorted to plane sections for the study of three-dimensional objects, even before these were codified. The solutions are rather simple for simple surfaces such as planes, cones and cylinders, and even the sphere, but become more complicated as the degree of mathematical complexity grows. Sometimes we must superimpose a grid on the surface in order to describe the form by means of a regular network of points, as series of plane sections that are orthogonal or radial with respect to each other (fig. 4).

Fig. 4. Students' geometric exercises on forms and surfaces in natural architectures

In reality, architects have always resorted to the use to models, even wooden ones,³ built according to the same constructive logic that they were intended to simulate, in a way that is analogous to how we create virtual models today, which are always based on compositions of geometric elements.

Virtual modelling no longer requires the use of Mongian projection to solve problems of representation and measurement, but in any case the construction of objects requires careful geometric control of solid forms and curved surfaces.

Once we know the rule (or rules) that govern the form and the relationships of its parts, it is no longer relevant if the instruments used for its description are pencil on paper, numbers and

equations, or a virtual model. But since at the very beginning in drawing, in architecture, there exists only an idea that grows in our minds with the support of geometric references, we always need graphic notes for visualising the various stages of this development.

Usually architects prefer the pencil while engineers prefer numbers – this perhaps is the most obvious difference between the two – but in either case geometry is used to identify the new forms.

Many of the figures that illustrate the present paper are derived from experience in didactics conducted during courses of architecture at the universities of Florence and Parma. The study of regular natural forms was proposed as an exercise in Drawing and Descriptive Geometry. The didactic itinerary for understanding drawing and scientific representation was defined by the search for a geometric scheme of reference for a formal synthesis of the architecture of regular natural objects (figs. 5, 6, 7). This undertaking allowed the students to investigate how geometry characterises natural architecture, and furnished as well a stimulus for approaching mathematics and the study of the increasingly complex surfaces that characterise recent developments in architecture.

Beauty and geometry

Since antiquity man has been fascinated and awed by the beauty of the natural world, and have lingered over the regular conformations of crystals, living creatures (simple animals, plants and flowers) or their parts,⁴ up to the Renaissance,⁵ when the human body was considered the maximum expression of natural perfection and the highest divine creation (fig. 8).

Figs. 5 and 6. Students' studies on geometric laws in architecture: natural and manmade constructions

Fig. 7. Students' studies on geometric laws in architecture: natural and manmade constructions

Fig. 8. Francesco di Giorgio Martini, human perfection in architectural proportioning

According to tradition, in treatises from Vitruvius to those as recent as Gottfried Semper,⁶ the origin of architecture was traced back to the imitation of nature, and for a very long time the formal inspiration for ornament and decoration were sought in the regular configurations⁷ of natural examples. But above all architects found the solution to specific structural problems in nature. The architectural orders are perhaps the prime, as well as the most famous, but still only one example among many, since nature offers a great quantity of models that respond to structural, formal and aesthetic problems.⁸ In spite of the passing centuries, what appears to be a game without any evident rational foundations is the repetitive reference to nature as a design model and a rule for aesthetic equilibrium, which led to the obsessive search for a rule of beauty based on geometry.

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 (fig. 9).⁹

Fig. 9. Analogies of statics in vertebrates and architectural structures

This 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.

protozoa forms and surfaces

Cilindro Onduloide Sfera Catenoide Noduloide
Cerchio Ellisse Retta Iperbole Parabola

regular solids in radiolaria

geometric equilibrium in cells duplication

Fig. 10. Geometric surfaces and solid forms in cells: soap boubles, protozoas and biological tissues.

Effectively, mathematical models were developed to simulate reality by means of numbers, but geometry, which refers to form, is a 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 (fig. 10).

Many centuries ago, Plato believed that all of reality could be traced back to two kinds of triangles, those found in the regular solids that symbolised the four fundamental elements. He didn't justify this, but he had to have been conditioned by the strong presence of geometry in natural objects. Much later, Kepler was fascinated by snow crystals and beehives. In more recent times science has explained the presence of constant angles in crystal structures through molecular chemistry, while regular organic forms are linked to the biological necessity cells, tissues and the growth of living organisms. Naturalists have explained that the Fibonacci series and the Golden Number effectively exist in plant and animal forms, because the mean ratio (Golden Section) satisfies the principle exigencies of growth, which is that of maintaining the same form and therefore the same harmonic equilibrium (as in the gnomon), important because a change in this equilibrium would require a search for a new vital equilibrium (fig. 11).¹⁰

Fig. 11. Spirals and growth, maintenance and deformation of form

D'Arcy Thompson¹¹ explained that the main problem of natural phenomena is always linked to efficiency and the search for the minimum output of energy. He explains and illustrates the problems of minimal surfaces and saturation of space with geometric models that are resolved by means of the most elementary regular solids.

Just as similar forms, from the smallest to the very largest, appear in the architecture of nature, in a way that recalls fractals, self-similar elements of different scales characterise creations of human design, and regular geometries give evidence of an equilibrium between the static symmetry of closed forms and the dynamic movement in relation to asymmetric forces that belong to growth and life.

The substance is different, but the concept is not too distant from the Platonic idea ... and even Leon Battista Alberti was right in some way: in fact, if there is divine perfection in the human body and it exhibits the proportions of the Golden Number, this depends solely on the fact that growth must be regular, except in the cases of error or accident, and the Golden Ratio – and only the Golden Ratio – can guarantee this requirement.

As a consequence, the study of diagrams of its formal phenomena in nature – on which classic thought is based, and therefore the development of all of modern science – facilitates the resolution of many design projects, especially the research for Alberti's *concinnitas*, which is satisfied in the harmony of parts expressed by means of shape and number (geometry and arithmetic). This allows the satisfaction of the principle requisite of classic architecture, that is, the Vitruvian triad of *firmitas, utilitas, venustas*.

Formal models for design

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:

- 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. 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 several (translation, reflection, rotation...) and can 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 diversity of solutions.

Growth is therefore 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 (figs. 12, 13, 14).

Radial division. 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 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.

Fig. 12. Regular grids and surface organization: students' studies on regular patterns

Fig. 13. Regular grids and surface organization: studies from Leonardo and Le Corbusier

Fig. 14. Regular grids and surface organization: Fritz Hoeger's ornamental brickwork

Linear continuity. Spirals derive from unidirectional linear growth that can be either planar or spatial, but which 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. 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.

The importance of the module

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, while spatial applications are more difficult, except in the imaginative fantasy as in the works of M.C. Escher's (fig. 15).¹²

Fig. 15. Regular grids and surface organization: M. C. Escher's studies about surface and spatial grids

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.

The spirals evokes continuity, and its shape, often conjoined to the Golden Ratio and charged with symbolic and aesthetic meaning, has always stimulated formal invention: we find it in designs for ornament and in architectural projects, where it satisfies the necessity of a continuous growth in space, such as in the Guggenheim Museum by Frank Lloyd Wright.

Double spiral grids are frequent in nature and are not unusual in architecture, as for example in the design of the surfaces such those in Michelangelo's Campidoglio in Rome or in the subdivisions of the domes of Guarini and Taut.

Fig. 16. Student study of irregular surfaces

Fig. 17. Student design developing from natural form

Conclusion

Thus we see that geometric elements are the principal design tools used to make ideas of a project concrete. We find confirmation of this when we compare the marvellous variety of natural objects with architects' imitations of them, and at the same time we find stimulation for new projects.

In imitating organic forms and structures, architecture shows its age-old relationship with primary geometric elements: numeric sequences controlled by unambiguous laws that characterise natural construction as much as built objects. As the figures for this paper show, drawing is an expression of geometry for understanding and describing form. With regards to architecture geometry communicates more clearly than words, because it becomes the concrete aspect of our imagination.

Notes

1. Several sheets of his sketchbook show human faces or animal bodies built up on geometric grids; see Villard de Honnercourt, *Disegni*, Jaka Book, Milan, 1988.
2. Before Descriptive Geometry was codified by Gaspar Monge in the eighteenth century as a graphic application of Projective Geometry, orthogonal views were used in plan and elevation drawing, as shown in many medieval projects and some archeological objects.
3. Wooden models has lost their importance because plane omology allowed easy and more economical solutions to of spatial length problems using ortogonal projection.
4. Ian Stewart, *What shape is a snowflake?*, Weidenfeld & Nicolson, London, 2001.
5. Luca Pacioli, *De divina proportione*, Venice, 1494.
6. Gottfried Semper, *Der Stil*, München, 1860-63.
7. Ernst Gömbrich, *The sense of order*, 1979.
8. Paolo Portoghesi, *Natura e Architettura*, Fabbri Editori, Milan, 1993.
9. D'Arcy W. Thomson, *On Growth and Form*, Abridged Edition, Cambridge, 1961.
10. Mario Livio, *The Golden Ratio*, Broadway, 2002.
11. Figs. 9-10-11 are from D'Arcy W. Thomson, *On Growth and Form*.
12. M.C. Escher, *His life and concrete graphic work*, Abradale, New York, 1982.

About the author

Michela Rossi Michela Rossi is a professor or architectural drawing and representation at the Architecture Department of the University of Parma, Italy. She earned her Ph.D. at the University of Palermo, discussing a dissertation that addressed the question of structure and ornament in historical and contemporary architecture. She teaches courses of descriptive geometry and architectural drawing, and pursues her own research on the characteristics of traditional architecture in Northern Italy, and on the transformations and historical evolution of landscape. She is author and co-author of several books, including monographs on Tuscan rural churches, on Renaissance *palazzi*, and on the network of rivers and canals in the Parma region.