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Research

Perception of Order and Ambiguity in Leonardo's Design Concepts

Abstract. Leonardo da Vinci used geometry to give his design concepts both structural and visual balance. The paper examines aesthetic order in Leonardo's structural design, and reflects on his belief in analogy between structure and anatomy.

Leonardo's drawings of grids and roof systems are generated from processes best known from ornamentation and can be developed into spatial structures assembled from loose elements with no need for binding elements. His architectural plans are patterns based on principles of tessellation, tiling and recursion, also characteristic of the reversible, ambiguous structures which led to Leonardo's further inventions in structural and mechanical design as well as dynamic representations of space in his painting.

In recent times, the ambiguous structures in the art of Joseph Albers, the reversible and impossible structures of M. C. Escher, the recurring patterns and spherical geometry of Buckminster Fuller and the reciprocal grids in structural design of Cecil Balmond display a similar interest. Computer models and animations have been used to simulate processes of perceiving and creating ambiguity in structures.

1 Introduction. Leonardo – Architect?

To recognise the extraordinary work of Leonardo da Vinci as architecturally relevant, his design should be evaluated through criteria of aesthetic value, programmatic and functional issues as well as the building performance. This could turn out to be a difficult task: in an absence of any built work, referring to Leonardo as an architect is not self-evident. Furthermore, his notebook *Codex Atlanticus* remained inaccessible for centuries and the influences he may have had on architecture from the Renaissance to present days is difficult to establish. As this fascinating personality also seems to have been disconnected from the majority of his academic contemporaries, his work has often been described as lacking solid argumentation; it is not surprising that besides being praised as a universal genius, the phenomenon 'Leonardo' has also been criticised as a mere scholarly obsession, continuously reinvented as a mythical archetype.

To consider Leonardo as an architect, his work should be studied in a broader context, including his drawings as well as writings, scientific explorations, inventions and paintings. Understanding his design methods and thinking could help reveal the complexity of issues he addressed as well as analogies with contemporary theory and practice.

Leonardo's biography reveals that besides being a brilliant innovator, he had more than a casual interest in architecture and engineering. An apprentice to the Florentine artist Andrea del Verrocchio, he received training in painting and sculpting, and gained excellent technical and mechanical skills. But it wasn't until his emigration to Milan in 1483 that this member of the Florentine painter's guild also began working on architectural and engineering projects and consulting for the Sforza court. Later, the multitude of his talents and interests were given support by the French King Francis I, with whom Leonardo remained appointed as the First painter, architect and mechanic until his death in 1519.

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The strength of Leonardo's architecture might lie in innovative conceptual thinking rather than excellence in practice. However, as some of his later studies of plans of cathedrals show, he also studied some of the very practical issues, such as the varying strengths of architectural elements (pillars, beams and arches) and invented a range of building tools. His plans and sketches display a tendency to mathematical perfection of structures in which every component part has an exactly determined position and performance – a concept appearing much later as Kenneth Snelson and Richard Buckminster Fuller's 'Tensegrity'.

Rather than examining the exciting possibility of reproducing Leonardo's architectural sketches as built structures, let us first try to analyse his conceptual drawings of patterns, design objects, architectural and engineering solutions. They offer insight into his understanding of order in both nature and design as dynamic and evolutionary. Analogies with some of the contemporary art and architecture as well as theories in perception and aesthetics can be established.

Leonardo's creative approach to problem-solving was unique in his commitment to test knowledge through experience and to rely on the senses to clarify experience. His willingness to embrace ambiguity, uncertainty and paradox clearly supported his innovative thinking. Leonardo's search for analogies between art and nature, between art and science, and between evidence and imagination allows us to seek analogies when researching the continuity of Leonardo's design concepts and the impact they may have had on modern and contemporary theory and design.

2 Leonardo's views on philosophy and aesthetics

The sense of balance and harmony in aesthetics can be analysed through numeric and geometric order. In the conceptual drawings Leonardo created for architecture and engineering, the use of geometry aims to provide mathematical perfection as well as structural stability. Both of these qualities imply visual stability, inducing a sense of balance and harmony.

But before examining the underlying aesthetic order of Leonardo's design concepts, let us first consider his philosophical background.

As much as Leonardo prided himself on not being a "learned ignorant" but a self-taught man, certain influences on his thinking can nevertheless be established. It seems that it was particularly by reading Cusanus and Alberti that he formed his views on the Universe and its laws, as well as of the correlation between mathematics (geometry in particular) and aesthetics.

As Dr. Tine Germ points out [1999], it was indeed Nicholas of Cusa (Nicolaus Cusanus, 1401-64), German humanist, scientist, philosopher, statesman and cardinal of the Roman Catholic Church who influenced the work of Leonardo. Leonardo seems to have read Cusanus and shared his views on humanism as well as on mathematics.

Mathematics is perceived by both men as the science that allows artists to understand beauty, as Leonardo confirms in the beginning of his *Treatise on painting* [1956]; it identifies harmonic relations and proportions between parts as primary criteria of beauty. In fact, beauty becomes a universal principle characterising nature, art and geometry.

In his work *De Coniecturis II* [Nicholas of Cusa 1972, vol. III], Cusanus presents Man as microcosm inscribed in a circle and a square – an understanding of the human body that goes beyond the medieval theories of Man and the Universe. Similarly, *De docta ignorantia III* [Nicholas of Cusa 1972, vol. I] relates the individuality of every human being as well as his cosmic definition to the concepts of circle and square.

By using the geometrical shapes of the square and the circle, Cusanus illustrates human individuality and uniqueness [Nicholas of Cusa 1972: III, I, 428]. In *De beryllo VI*, man is referred to as *figura mundi* as well as *mundus parvus* [Nicholas of Cusa 1972, vol. XI], a symbolic figure and an anatomical study at the same time, clearly influencing Leonardo's 'Study of human proportions' (the Vitruvian man).

Leonardo's interpretation of Vitruvius's concept of man is both a proportion study and a manifesto on symbolic correlation of man to his body parts, the parts among themselves, as well as man to the universe. *…e l'uomo è modello dello mundo*, he writes [Richter and Richter 1939: II, 242]. The square manifests the divine nature in its limited form – Leonardo explains it as human nature; the circle is the symbol of infinity, which represents absolute truth; to Leonardo, both have the same essence.

Other Renaissance architects also considered the human being to as measure of all things. However, as Wittkower states, this is not an evidence of an anthropocentric understanding of the world [Wittkower 1988; Steadman 1979: 17]. As man was made in the image of God, the proportions exemplified in the human form reflect both the divine and cosmic order. Such a concept of proportions can also be found in drawings by Francesco di Giorgio in his *Trattato di architettura*.

This viewpoint is also reflected in the nine solutions for the tiburio of the Milan cathedral (which was also his most complete project), which Leonardo designed as a "doctor-architect", treating the body of the building and its illness. The notion of building as a body must have been derived from the concept describing the universe as consisting of self-similar units with its characteristics reflected in all its component parts.

Cusanus was the first neo-Platonist to determine philosophically the newly-defined role of an artist as colliding with the notion of a philosopher. His work entitled *De docta ignorantia* is echoed Leonardo's attitude towards the academics: he may have been a great thinker, but Leonardo preferred to mock the learned and rely on his own experience and intuition. In his belief, a true artist was necessarily also a philosopher, because philosophy and arts both deal with nature and its truth. It is through art that the causes of natural phenomena and their laws can be explained and illustrated [Leonardo 1907: 54].

Following his frequent research in dynamics and mechanics of water, many of his drawings of physical phenomena, such as vortexes and their structure, remained present in his attitude towards the aesthetic order in patterns and ornaments. A similar thought appears in the architectural theories of the 1990s by authors such as Greg Lynn [1998], who draw inspiration for architectural form generation from fluid dynamics.

3 Order as a dynamic concept in nature and art

3.1. Order and ambiguity. Leonardo's close observations of natural phenomena led him to an understanding of the dynamics of order and chaos in nature. His artistic and technological conceptualisation reflects the evolutionary principle of cyclical growth and destruction.

Many theories refer to order as a dynamic rather than a static concept, a unity of opposites producing balance. In Cusanus, God – the supreme harmony – is described as *coincidentia oppositorum*. Cusanus also strongly influenced Alberti's concept of beauty based on numeric harmony of proportions of micro- and macrocosm.

Leonardo's attempt to define the inherent order in natural structures in order to understand the macrocosmic level of universal logic is echoed in some of the contemporary theories addressing the evolutionary principle of growth through unifying elements in opposition. The principle of analogies in micro- and macrocosm also appears in contemporary theories of emergence and chaos having their roots in natural sciences.

Order is defined as the state of a structure in a dynamic system with an inherent latent chaos; intrinsic influences can trigger a dynamic imbalance which leads to a chaotic state of the structure. Once such a state has been reached, the structure's tendency is to return to the initial state of order. Therefore, order can be described as a shifting state among chaotic formations.

A concept that is nearly synonymous with order, harmony and proportion of structural modules, is symmetry. It indicates an array of elements in relation to a central axis or a point, or a characteristic of an object split into two identical parts by an axis or a plane. Visually, it signifies balance and harmony as well as matching dimensions of modular elements.

In the introduction to Vitruvius's *De Architectura Libri X*, Daniele Barbaro [1556] explains symmetry as the beauty of order, a harmonious relation of a part to the whole where the matching measures indicate modularity.

However, symmetry can also be defined as a hidden dynamic: the difference between the given structure and one that has undergone a symmetric transformation (for example, mirroring, cyclical rotation, glide plane reflection) cannot be perceived because the structural modules are in balance. The result of such a transformation shows no obvious changes in basic quantities of the structure. Therefore, a structure is symmetrical if it revolves onto itself after a transformation. Natural configurations (for example, crystalline chemical structures) are symmetrical.

Self-similarity is the characteristic of fractal scale: any natural or artificial structure, in which every part is a copy of a part of the structure as well as a copy of the entire structure, is self-similar. Any symmetry that does not change as a result of change in size, is self-similar: smaller parts mimic bigger parts that are similar to the entire structure.

Natural systems behave unpredictably. In fact, nature appears to be a chaotic system where order is present in its smallest components, which grow algorithmically and sum up intrinsic variations, ultimately resulting in a high degree of complexity. Such dynamic, non-linear systems self-organise up to a critical point when an intrinsic event provokes a chain reaction that leads to chaos, that is, where the feedback of those intrinsic events adds up to a drastic change in the system. Complex dynamic systems are said to be composed of interactive elements and are very sensitive to intrinsic factors.

The building blocks of such systems are fractals – geometric shapes whose dimensions have a non-integer value, relating to the degree of folding the particular pattern or shape has. An algorithm based on a geometric motif can evolve into a fractal – a self-similar structure that offers infinite irregularity at any fixed scale. Fractals grow into diverse complex structures following simple iterative equations. Modular systems in architecture have a similar principle: basic modules grow into larger structures by multiplication of modules according to a simple algorithmic rule.

Like modular systems, the Fibonacci series is in fact a scale of self-similar relations in which the values of fractions among the subsequent members of the series approach the golden ratio. The Fibonacci series gives insight into growth by accumulation. Perhaps it is not surprising to find it in both organic nature as phyllotaxis, and in art and architecture as a blueprint for harmony.

3.2. Leonardo: learning from nature. Using his ability to see analogies, Leonardo studied order in nature as a system to be reproduced in his creative work. The use of geometry in his design concepts is aimed at providing mathematical perfection and structural stability, but one could assume that it also provides visual stability and therefore aesthetic harmony, which will be discussed in the following sections. Leonardo wrote a book on the elementary theory of mechanics, published in Milan around 1498 [MS 8937, Biblioteca Nacional, Madrid], in which he warns of the dangers of facing confusion, should one not know of the supreme certitude of the mathematics. His main influences were probably the geometric nature of Cusanus's philosophy, Alberti's *De Re Aedificatoria*, as well as his façade motives and decorative patterns, particularly Santa Maria Novella. Other important influences include Piero della Francesca's *On Perspective in Painting*, Luca Pacioli's *Divina Proportione* (which Leonardo illustrated) and the geometric nature of Islamic patterns and ornamentation, brought to Renaissance Italy through a vivid commercial and cultural exchange.

Cusanus claims that artists mimic nature, but without copying its shapes, forms and visual patterns. It is the spirit that guides and determines the artist. Empirical and sensual experience as well as the underlying order in natural forms is fundamental to the process of perception and cognition: *La natura è piena d'infinite ragioni che non furono mai in isperienza* [Richter and Richter 1939: II, 240] and *Nessuno effetto è in natura senza ragione; intendi la ragione e non ti bisogna esperienzia*" [Richter and Richter 1939: II, 239].

Leonardo similarly described nature as the *maestra dei maestri* [Richter and Richter 1939: I, 372]; he claims a work of art is best when it approaches nature. Studying anatomy was therefore of great importance for his solutions in art and design.

Leonardo worked empirically and studied the impact that nature has on direct sensual experience. Yet in his *Treatise on painting* [1956], he admits that the aim of creation is the artist's vision – a vision that is always already inherent in the Universe. He writes:

> *Sel pittor vol vedere bellezze, che lo innamorino, egli n'è signore di generarle,… et in effetto, ciò, ch'è nel' universo per essential, presentia o immaginatione, esso l'ha prima nella mente, e poi nelle mani.*
>
> (if a painter wants to see beauty that enchants him, he is the master to generate it, … and that, which in universe exists as an essence, a presence or

> an imagination, first exists in his mind and later in his hands) [Leonardo 1956, fol. 5r, p. 24],

a thought that was repeatedly stated by Cusanus: *… nam omnes configurations sive in arte statuaria aut pictoria aut fabrili absque mente fieri nequeunt. Sed mens est, quae omnia terminat* (...no artefact in sculpture or painting or craft can be created without the mind. The mind is that, which determinates everything) [Cusanus ---- : VIII, 534].

Leonardo described the universe as a mechanical entity; this is reflected in the way he designs structures and deals with forces, resulting in engineering solutions very unlike the static solutions of his contemporaries. Leonardo's inventions, according to Buckminster Fuller, reflect a universe that is dynamic in every aspect.

In his quest to discover a universal order and the underlying principles of micro- and macrocosmic harmony, the synthesis of anatomy and mechanical engineering is probably Leonardo's most powerful concept.

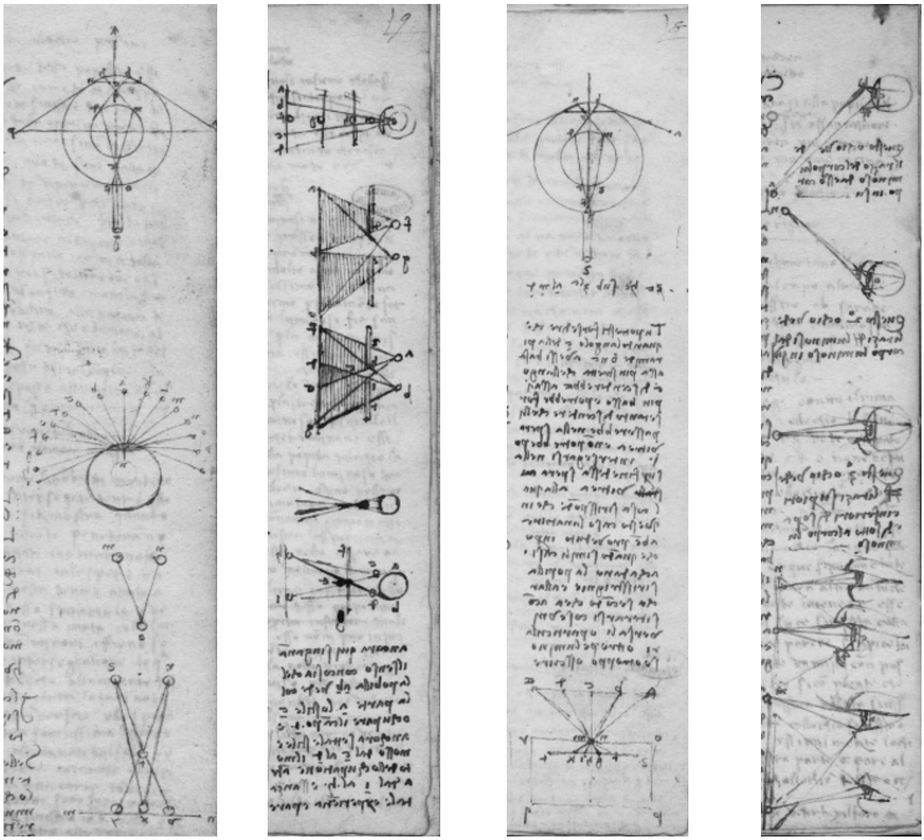
All his design concepts show an underlying organic order, a synthesis of the natural and the man-made, of structural logic and aesthetic sensibility. The drawings of the manuscript Windsor RL 12608r reveal his simultaneous research in architectural details and anatomic dissecting. In many of the drawings in *Codex Atlanticus*, machines and engineering devices are conceived in imitation of biological organisms and their behaviours. This translation of movements of the organic to the machine world reveals his attempt to rationalise forces in nature through the use of mathematics.

This approach resonates in Buckminster Fuller's interest in biological forms as representations of the "'microcosm in the macrocosm"; it is also reflected in his structural design, such as the faceted shape of the Expo sphere; this structure mimics a marine micro-organism first described in D'Arcy Thompson's *On Growth and Form* [1992] and admired by Umberto Eco because of its ambiguous character [1967: 9].

Engineer Cecil Balmond similarly argues that by looking at Nature, we discover a pattern-maker of infinite skill. The simple and the complex inform each other in a collective exchange where their hierarchies are lost in an ultimate loop. Nature is also information, its algorithms a combination of iteration and a tendency for coherence.

4 Viewing and seeing

4.1. Leonardo's theories of vision. One of Leonardo's principal drivers of creativity was the sharpening and perfecting of his senses to enhance his empirical demonstrations, which explains his obsessive research in anatomy. Following the total solar eclipse on 16 March 1485, Leonardo began not only to study the human eye, but also to design optical instruments, as he was convinced that the human eye errs less than the human spirit. Exploring human vision helped him understand the moving nature of light, and led him to the discovery of its proper speed which he tried to calculate. His treatises on optics focus on the anatomy and functions of the human eye; they can be regarded as attempts to understand the mechanisms of visual perception. As much as they seem remote from today's understanding of vision, they were successfully applied to his experimental and creative work.



a) Studies of the way in which the eye sees objects. Ms. D, fol. 8v

b) Studies of the mechanism of optical illusions. Ms. D, fol. 9r

c) Reception of the image in the eye and schema of the intersection of visual rays. Ms. D, fol. 8r

d) Studies of luminous rays produced not by the object but by the pupil. Ms. D, fol. 9v

Fig. 1. Leonardo da Vinci's studies on optics

According to David C. Lindberg [1976], the foundation of Leonardo's theory of vision is his theory of radiation and the radiant pyramid. Objects send their images or likenesses (*similitudini*, or species) in all directions into the surrounding transparent medium. The species converge along straight lines and form pyramids that have their base on the object and their apex at every point in the medium. This way, Leonardo believes, each body by itself alone fills the air around it with images; this air receives the species of bodies that inhabit it. It is interesting to note that here again Leonardo states that species are self-similar: all throughout the whole and all in each smallest part; each in all and all in the part.

In Leonardo's view on perspective, all objects transmit their images (species) to the eye by a pyramid of lines which start from the edges of bodies' surface; converging from a distance, they are joined in a single point situated in the eye, which is the universal judge of all objects (fig. 1).

The images spread out in a circular way from an object – as in the case of circles spreading out from the point of impact of a stone thrown into a volume of water.

Leonardo's great contribution to visual theory was his comparison of the eye to a camera obscura, so that the intersections of rays from a visible object must occur within the pupil. This way an inverted image is formed – unless a second intersection appears, caused by reflection or refraction. But the retina is not considered to be a screen, analogous to the back of a photographic camera, onto which images are projected.

Leonardo's critical observation, supported by experimental demonstration, also made him aware of the variable size of the eye's pupil.

Rejecting the perspectivists such as Brunelleschi and Alberti, he argued that the seat of visual power is not situated in a point and is not at the apex of the visual pyramid. He believed the pupil of the eye has a visual virtue in its entirety and in each of its parts and demonstrates that the eye perceives from more than one point.

Later, he claimed that vision occurs only through rays emanating from a point; only radiation falling anywhere within the pupil would be perceived. The judgment of the visual input supposedly resides in the place where all senses meet. Today, this is known as the visual centre in the cortex where cognitive process begins once the visual input has been processed.

Leonardo's studies and experiments in anatomy allowed him to elaborate his own theories of visual perception and representation, and were fundamental to his further observation of order in nature and art.

Today, theory of visual perception is based on the diffuse reflection of light in the process of perceiving images of the environment. Visual perception is the principal active system for retrieving information from the environment and functions as a process of creating images through our sensorial apparatus.

The human retina was once considered to reproduce reality in a way a lens or a mirror would. Today, research shows that complex information perceived via sensorial stimuli become meaningful after they have been processed in the brain, that is, after having been placed in a context of neurological activities.

In psychology, Gestalt theory, formed in the 1920s by Kafka, Koehler and Wertheimer, had a great impact on art and design for the decades to come. It proved that the hierarchy of image and background is the primary principle of organisation of sensorial stimuli. The image is defined as the dominant, coherent element in a visual field, whereas its background (also called the context) is defined as ambiguous, less ordered, secondary and diffuse. It is not surprising that in visual perception as well as aesthetics, theories are built upon similar relations of hierarchy: a whole is more than a mere sum of its component parts, distinguished from the parts by its formal and semantic quality.

According to Gestalt theory and particularly James J. Gibson, the organisation principles of perception reflect the isomorphic configuration of nervous processes (see, for example, [Gibson and Hagen et. al 1992]. Human mechanism of the organisation of perceptive stimuli as well as the constancy of perception is in direct relation to our physiological needs, allowing order in a system to be spotted immediately.

In certain situations however, a clear distinction between the figure and the background is less evident, such as when viewing ambiguous or so-called 'impossible' structures that correspond to the notion of symmetry break in structures.

4.2. Hyperseeing: reading ambiguity. Referring to symmetry and order as 'latent chaos' indicates that there must be a thin line between the two extremes.

Symmetry in emergent theory indicates a lack of interaction with external forces and the context. A structure with such qualities is sensitive; it is inevitably subject to dynamic forces that produce irregularities which sum up to chaotic behaviour. When this occurs, the latent chaos in a symmetric structure becomes apparent; the so-called symmetry break creates dynamics in the structure and becomes the focus of attention. This irregularity can be a broken sequence or continuity, a visual accent, or any other disturbance in the structure. The tendency, however, is for the behaviour to become regular again; therefore a symmetry break is not considered a loss of organisation, but rather a chance for growth and reorganisation within an open, flexible, adaptable, polymorph system. Symbolically, it brings in a dynamic conflict and the notion of opposition and duality.

Ambiguity is an example of such chaotic behaviour. In visual perception, stability and constancy of a perceived set of visual stimuli can be destroyed when misinterpreted.

When we attempt to understand ambiguous structures, a dynamic, relative, shifting experience of illusion occurs as an error in the process of transmission of information along the system. Ambiguous structures have more than a single possible interpretation and always appear as a shifting sequence of interpretations, that is, in an inverse optics. Deleting redundancy from ambiguous elements enables a correct interpretation.

Gestalt theory explains the multistable perception of ambiguity as the dynamic, oscillating perception of ambiguous structures having two equally dominant perceptive organisations that cannot be semantically resolved. In an ambiguous structure, perception shifts between the figure and the background can be created: if the eyes of the observer remain fixed upon an object, the rest becomes background. If the figures are equally strong both structurally and semantically, the observer's attention shifts and so does the interpretation of a figure (an object) against its context. Optical illusions are examples of such ambiguity in visual perception. They occur when an image lacks a hierarchical differentiation of object from background; such a situation does not provide either sufficient information for the brain to decode a single message, or to recognise both interpretations simultaneously, which results in the oscillation between two options, as mentioned above.

The synergetic model of perception describes such dynamic features through pattern recognition: when attention is saturated, only two prototype ambiguous patterns (constants) are said to remain in our memory: our perception resolves this situation by shifting between the two extreme interpretations.

Ambiguity usually indicates weakly organised visual stimuli; it should be recalled that in Gestalt theory, stimuli are said to be organised by sensorial assimilation following the principles of figure versus background as well as group formation (using methods of organisation such as proximity, similarity, good form, symmetry, enclosure and common destination of stimuli). However, certain principles of visual organisation, such as overlapping or diminishing size with distance, which are also commonly used in perspective construction, can have an impact on our perception of depth, distance and space. It is the phenomenon of the constancy of perception that keeps visual organisations stable. The human capacity to recognise colours, sizes, shapes, and light as constants – regardless of minor contextual influences on the perceived image – means that structurally strong organisations can remain stable, whereas weaker structures dissolve and become ambiguous.

One such ambiguous structure is particularly intriguing for artists: the so-called ‘impossible’ object is a configuration that appears as a result of an intentionally created ambiguity. This phenomenon is at the intersection of disciplines such as art, psychology and mathematics. Multibars, such as the Penrose ‘impossible’ tribar, are fascinating: here, a contradiction in our interpretation of the perceived object is noticed but is not dismissed as materially impossible. Our brain tries to interpret it as a three-dimensional object in Euclidean space, with straight edges, instead of interpreting it simply as a two-dimensional object drawn on the paper plane. There is no particular element signalling the perception shift or a break that would trigger the “break-spotters” and “continuity” is reported, making the impossible even more obvious. In the interval between fixations, certain characteristics of the object appear as their opposites (for example, convex becomes concave), which we do not normally experience in real objects. This phenomenon has inspired many of Escher’s drawings and watercolours.

In mathematics, the four-dimensional space is referred to as hyperspace. According to Nat Friedman [2001], the method of observation in hyperspace is ‘hyperseeing’. In hyperspace, one could hypersee a three-dimensional object completely from one viewpoint. Open forms and topological geometric configurations (knots, for example) are particularly interesting for such observations, and viewing ambiguous structures would benefit from this method as well. To entirely see a n-dimensional configuration from a single viewpoint requires stepping into an $n+1$ dimension. Theoretically, this would allow us to see every point on the configuration, as well as every point within it. This approach to viewing has often been used by artists such as Picasso and Bacon, showing multiple views of a configuration in the same representation, and is an essential tool in architectural design and representation, shifting from plan and section to volume and animated views.

4.3. From plan to volume: architectural abstraction, perception and representation of space. Hyperseeing can also be used to describe the ambiguous nature of many of Leonardo’s drawings and paintings.

The mechanism of hyperseeing, optical illusions, linear perspective and depth clues can also be used to produce an illusion of space in the representations of a three-dimensional space on a two-dimensional plane. Illusions of depth and movement are used in painting and architectural representation (for example, perspective) to simulate a two-dimensional plane that opens into higher dimensions. In the same way, a two-dimensional pattern containing ambiguity and illusory space can open up into a three-dimensional structure. Leonardo’s conceptual drawings of ornaments and architectural structures in *Codex Atlanticus* frequently rely on this mechanism.

In art and architecture, perspective is used as a geometric tool for selecting viewpoints and structuring space in relation to an idealised body. Brunelleschi and Alberti introduced it as a projective tool as well, and as a conceptual scheme supporting theories of visual perception. Perspective drawings are based on the illusion of depth (that is, the illusory three-dimensional space) and overlapping to represent space on a two-dimensional plane; on the other hand, axonometric projections enable an overview of an infinite space. Perspective depends on a single viewpoint, whereas the neutral space of an axonometric projection suggests a continuous space filled with elements in motion. The ambiguity and reversibility of axonometric space allow representation with multiple viewpoints. Unlike the case of perspective viewing, the observer focuses on an object in an indefinite spatial-temporal field.

In Leonardo's representations of architecture, the relation between plan and volume is particularly interesting. His bird's eye perspective drawings of churches indicate his attempt to step away from the limitations of a single viewpoint by using a nearly isometric projection. Being a visionary, he applies spatial parameters that could not be measured or empirically verified with instruments of his time. His landscapes are created using a series of views departing from a single viewpoint.

The landscape in the background of Leonardo's painting of the Mona Lisa, for example, has multiple horizons, with details so accurate that they defy the logic of the linear perspective. The background consists of several plans that were painted sequentially and can also be viewed simultaneously. The entire set appears as if shot with multiple film cameras. Adding to the dynamics and ambiguity of the background, the portrait itself reveals an ambiguity in the shifting facial expressions of the portraitee, achieved with the help of the blurred outlines and colours of the sfumato technique.

Leonardo's use of spatial elements and multiple horizons is also close to the technique used by the German master Albrecht Altdorfer (1480-1535). His multiperspective approach to landscape painting in his canvas *The Battle of Alexander* from 1529 (Alte Pinakothek, Munich) allows viewing of a multitude of details from a single point on the horizon. It gives the viewer the impression of looking at the set from a great distance (as if from high in the air), yet being present at the same time in the mass of bodies, both human and animal, at all the key viewpoints. The painting can be interpreted as having an omnipresent observer situated both in the sky and on the ground.

Conventional architectural representation tends to frame a moment in time but cannot represent the forces shaping it and allowing all those subtle shifts between Euclidean dimensions that take place in a dynamic system. Computer animation integrates the dimension of time into architectural representation; it shows an evolutionary environment in which processes and their forces shape the built structure.

5 Dynamic principles in Leonardo's design

The timelessness of Leonardo's inventions is reflected in the way he adopted universal principles of mechanics and anatomy to create dynamic structures. The design methods used in his sketches and in his graphic, ornamental, structural and mechanical designs were inspired by his investigations in morphology.

5.1. Dynamic order: rhythm, sequence, pattern. The discourse of architectural representation and composition has benefited from the continuous research of mechanisms of human perception. Design concepts can be developed based on rules of visual perception; vice versa, certain principles of visual organisation (for example, overlapping and diminution of size with distance) have been demonstrated to influence our three-dimensional perception strongly.

Visual perception in art and architecture is considered a variable, but geometry on the other hand provides empirical foundations: it defines relationships among elements of a composition.

In the design vocabulary, symmetric transformations – rhythm, variation, number, measure, proportion, periodicity and modularity, repetition, as well as translation, rotation, and reflection – are used to generate patterns or spatial concepts.

Human creativity relies in large part on our ability to recognize patterns, which can be compared and matched with ones previously memorised. These patterns can manifest as different types of sensory output, making analogies among disciplines possible.

The elementary means of creating patterns and a sense of order in a structure is the process of repetition. According to Matila Ghyka [1971], rhythm can be described as observed and recorded periodicity. Periodical repetition of a motif or a pattern introduces a sense of movement and dynamics (that is, the dimension of time) into structure. Rhythm is one of the basic aspects of energy in time, creating patterns and sequences of form with specific frequency. It emerges from iteration and variation, as well as contrast, such as figure versus background.

In any rhythmical sequence, a pattern is produced when a motif appears. A very regular pattern can be quickly perceived because of the way visual organisation functions: irregularities such as ambiguity are easily spotted since, from an evolutionary viewpoint, they indicate change and possible danger.

5.2. The dynamic order of Leonardo's lattice grid. Examining the aesthetic order in Leonardo's patterns, ornaments and design concepts, particularly the plan of a roof system as appearing in *Codex Atlanticus* gives insight to the nature of perception of order and ambiguity as Leonardo saw it (fig. 2).

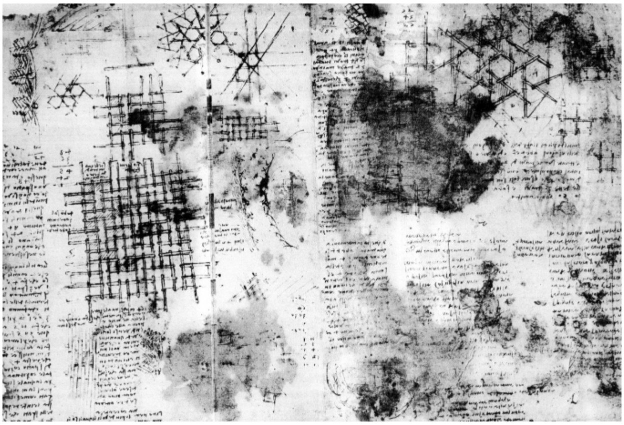


Fig. 2. Leonardo da Vinci, study of a wooden roofing made of parts that fit together. *Codex Atlanticus* fol. 899 v

The rectangular lattice structure appears in *Codex Atlanticus* fol 899 v as a study of wooden roofing made of parts that fit together. The lattices are tiled using a monotonous repetition with overlapping endpoints rotated at 90°. Overlapping (transposition) is used as a method of transformation that develops periodicity, regularity and rhythm in the pattern. By imitating plaiting and weaving, the pattern of the structure displays modularity and self-similar growth similar to the iterative order found in the generation of emergent structures. In Leonardo's drawings, the iteration of a fixed set of elements (beams) with a recombination (rotation and overlapping) creates a diverse and variable, yet modular structure.

Leonardo uses overlapping to develop a possible dome structure out of a grid. Here, the principle of overlapping has another interesting effect: as later shown by Gestalt theory, certain principles of organisation of visual stimuli in any two-dimensional representation can be used to create the illusion of depth, distance and space. Overlapping is a strong visual clue: it indicates relations among elements that are distributed hierarchically according to depth, that is, their location in an illusionary three-dimensional space. This technique has been extensively used in painting.

Leonardo's sketches demonstrate an aesthetic order derived from compositional processes in ornamentation, plaiting and weaving, featuring compositional methods that involve symmetry. Achieved by applying one or many of the three crystallographic principles, they involve shifting – through translation, rotation, reflection, for example – as well as tiling. The symmetry break, characteristic of ambiguous structures, is frequently used by Leonardo in his multi-perspective approach to landscape and portrait painting mentioned earlier. In Ernst Gombrich's terminology, such dynamics can be described as an exchange of restlessness and repose [1979: 120-126].

Although appearing symmetrical, the lattice structure drawn by Leonardo contains a symmetry break that introduces a dimensional transition from a two-dimensional planar image to a three-dimensional space. A perceptive shift takes place among the recursive elements that make up the structure. An illusion of stepping into the third dimension from a two-dimensional plane appears due to the ambiguity produced by overlapping as well as shifting of the depth clues. This ambiguity is perceived as oscillation between the convex and the concave, with shifting dimensions due to the confusion that the viewer of this drawing senses between the back and the front side of bars. Today, we refer to this phenomenon when describing the two-dimensional projection of a wireframe cube or the unstable perception of a hypercube. The illusion of continuity in which our perception follows a loop without noticing the twists (the symmetry breaks) gives this iterative structure its ambiguous dynamics (fig. 3).

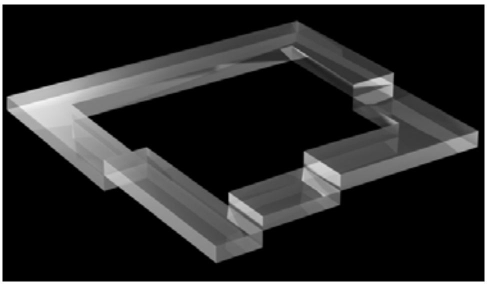


Fig. 3. Illusion of a continuous structure. Laurent-Paul Robert, 2003

In *Codex Atlanticus*, a number of drawings can be found that display designs imitating patterns, knots and plaits, details in wooden structures, the puzzle-like connection details of wood, chain members, intarsia, bridges (such as the wooden bridge on display in Vinci, barriers and birdcages. The design of the growing grid of the roof system may have been derived from Leonardo's interest in problems of continuous interlacing. This research has initiated the publication of a series of knots called 'Academia di Leonardo da Vinci' as a response to complex interlacing patterns adapted by Italian craftsmen from Islamic examples. Similar to textile design techniques, the aesthetic order of the structure is derived from processes used in ornamentation, plaiting and weaving (for example, linking, vaulting, overlapping). The construction of this roof system does not rely on additional binding elements; it is conceived as a self-revolving, self-supporting and continuously evolving structure.

The pattern of the roof system that Leonardo proposed was most probably inspired by studies of knots and puzzle-like structures and textures. Its approach is similar to his many mechanical engineering and defensive devices. Leonardo offers a dynamic solution to a static problem: forces within the structural beams of the dome are distributed using overlapping and linear transformations. He frequently used the principle of grasping physical forces through the rhythm and geometry of structure. His research in mechanical structures and devices, as well as water, revolved around pattern analysis that influenced his design concepts.

From an architectural perspective, the relation between plan and volume in Leonardo's design is particularly interesting. The roof plan is a two-dimensional abstraction of a three-dimensional structure, yet it functions as an ornamental pattern: its ambiguous character creates a visual shift, a seamless transition from plane to space.

Due to the temporary inaccessibility of Leonardo's drawings and an absence of built work, his influence on architecture is considered minimal, yet some of twentieth-century art and architecture displays similar interests.

The principles of growth and expansion from the second to the third dimension using overlapping and self-similarity can be found in many of M. C. Escher's graphic works. Fascinated by the concept of bounded infinity, Escher tried to reproduce growth through iteration.

The triangular variation of Leonardo's periodical pattern of the roof system (as in fig. 2) is based on superimposed overlapping beams that create an ambiguous pattern with two possibilities of interpretation. The pattern produces an illusion known from the previously described perceptive loop of the 'impossible' multibars, particularly the Penrose tribar. Each new situation that the eye encounters when following the lines of the pattern causes a re-adaptation of the interpretation, while the twists are not at all perceived.

Escher achieves the same optical illusion of a continuous structure that follows a perceptive loop (as in fig. 3) in his lithograph *Waterfall* (1961) inspired by the Penrose tribar, in *Ascending and Descending*, and in *Belvedere*. When observing the structure and gliding along the sides of the object (or the falling water), its impossibility, or the mistake, cannot be perceived. But after having completed the cycle of viewing, the shift takes place in the interpretation of distance between the eye and the observed object. Escher explained the impossible triangle as being fitted three times over into the picture. The Penrose tribar illusion contains ambiguity in its triple warp of the structure between convex and concave.

Whether the creation of perceptive shifts in Leonardo's lattice pattern was intentional or not, it is important to note that the subject of ambiguity is addressed too frequently in his work to be random. He studied it systematically, as is evident in the right bottom image on the MS H fols 32r – 33v and fol 35r (fig. 4). Here, a lack of a distinction between figure and background (that is, the front and the back edge and planes of the cubes in the arrangement) creates an inversion in the orientation of the cubes that takes place after a few seconds of focused viewing. An ambiguity of convex/concave in this repetitive structure is created.

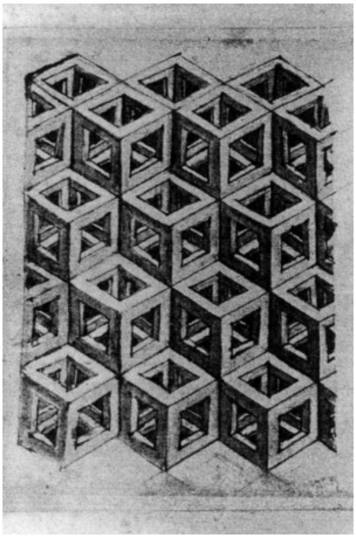


Fig. 4. Leonardo da Vinci, studies of convex-concave ambiguity in an ornamental structure. MS H ff 32r-33v, fol. 53r (detail)

Fig. 5. Structure with a convex-concave ambiguity (an interpretation of a detail from Josef Alberts, *Trotz der Gerade*, 1961). Laurent-Paul Robert, 2003

Due to this uncertainty, the two-dimensional structure depicted introduces an illusionary space drawn in an axonometric projection. The case is similar to the Schroeder illusion with the inversion of a staircase. Even though the visual focus remains, the interpretation shifts from frontal (standing) to backwards (hanging) in a continuous loop.

An analogy can be made with the impossible or irrational cube in the Necker illusion. This impossible object is a two-dimensional drawing of a cube, seen in an axonometric projection with its parallel edges appearing as parallel lines in the drawing. The seemingly consistent figure of a wireframe cube contains ambiguity: its overlapping opposite corners are joined together, resulting in a confusion between the back and the front of the structure. Its top and bottom parts, when viewed separately, appear to be a regular cube. If viewed simultaneously, the image seems to twist because the information is incomplete and lacks the details necessary for a single interpretation.

The space within the image of the cube appears to be warped. This warp is created by half of the cube being rotated 180° and mirrored. The interpretation of the cube oscillates between pointing forwards and backwards.

The same ambiguity is used in *Belvedere* by M. C. Escher in the impossible structure of the tower's upper floor (a character contemplating a Necker cube is also featured). Escher's encounter with the writings of Gestalt psychologists introduced him to the ambiguities inherent in figure-background relationships, the two-to-three dimensional ambiguity on a flat surface, as well as ambiguity of the reversible cube and of multiple perspectives.

Introducing movement into two-dimensional representation of a three-dimensional space through hyperseeing also characterises the work of Josef Albers. In his series *Trotz der Gerade* (Despite the straight line), influenced by Gestalt theory, a perceptive shift between the convex and concave interpretation is produced in the representation of the cubic structures. Albers demonstrates that inversion and permutations that are rich in ambiguities can be achieved with even the simplest elements (fig. 5). The subject of optical illusions, particularly the Necker and Schroeder ambiguities, has also been explored in the *Graphic Condensation* series by Francesco Grignani.

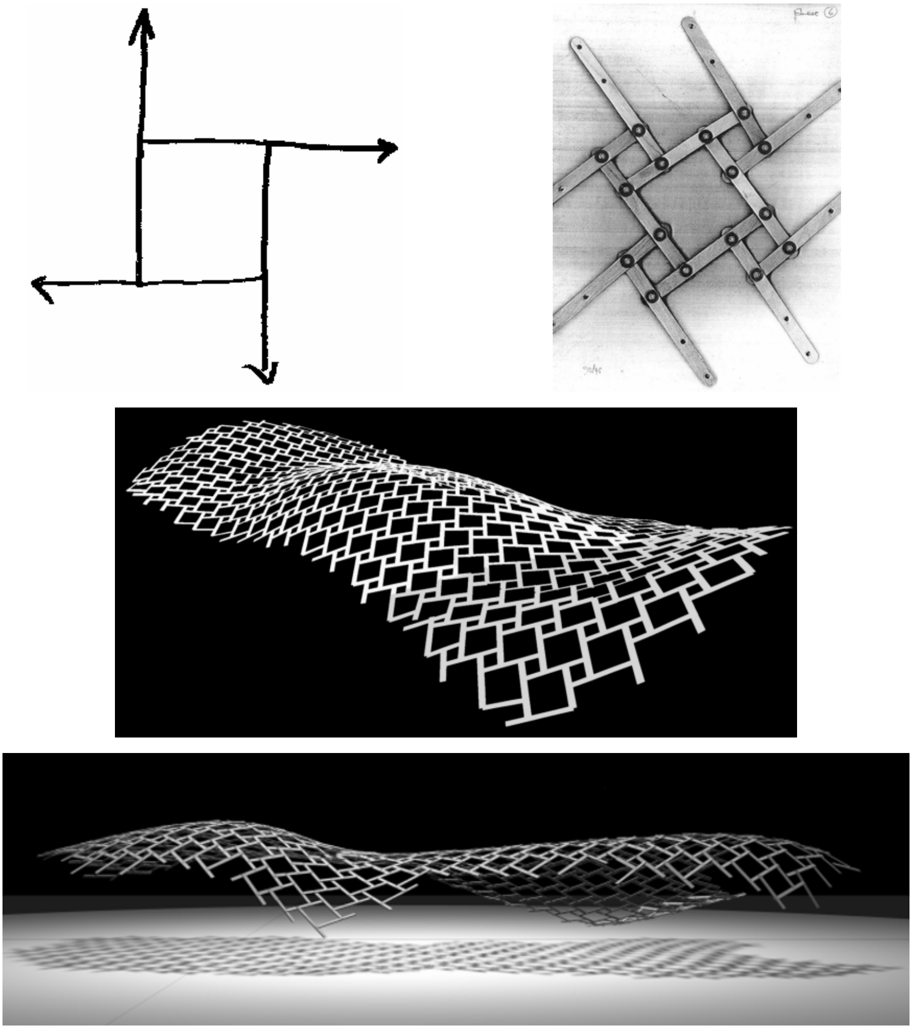


Fig. 6. Structural system: Reciprocal grid shell structural system for Forest Park Pavilion, St Louis, Missouri, USA. Architectural design by Shigeru Ban for Forest Park Forever. Structural concept and integrated design by AGU – Cecil Balmond, Charles Walker, Martin Self, and Benedikt Schleicher First concept phase 2004; scheduled completion 2007. © Sketches and photographs: Cecil Balmond; © Computer renderings: Advanced Geometry Unit – Arup

5.3. Reciprocal grids: a dynamic equilibrium. Leonardo's drawing of the overlapping grid can be translated into a three-dimensional structure assembled from loose, straight elements, when the middle point of one element is connected to the endpoint of another one. This pattern is extended using a simple iterative method, linking and interlacing. The beams represent the linking lines that cross above or below each other and thus produce a three-dimensional arrangement.

The overlapping grid has historical precedents in the spiralling poles of the native North American tepee and the "Rainbow" bridges of China's Song dynasty. Studies by the medieval master builder Villard de Honnecourt also described reciprocal structures that would allow floors and ceilings to be built from short beams.

Leonardo's lattice and triangular grids are in principle reciprocal grids. Elements arranged in a mutually supporting pattern create reciprocal structures. Normally an area is spanned using a grillage or by a hierarchical system of primary and secondary beams. But in the reciprocal grid, a network of individual elements shapes the load-paths in nested loops. The reciprocal structure is less efficient than an equivalent continuous grillage but because no bending loads are transferred between elements, their connections can be very simple.

Balmond argues that, conceptually, using elements that are too short for a continuous transmission of load in a straight line is nevertheless interesting: an interruption, a *staccato* appears in the assembly of the grid. Using a reciprocal arrangement of one member being fed into the other, the grid moves so that a cascade effect is developed.

Working with architect Shigeru Ban, Balmond developed the structural concept and integrated design for the Forest Park Pavilion in St Louis using the overlapping grid principle. Instead of the regular repeating grillages, this reciprocal grid shell has an alternating pattern of large and small squares. Balmond describes it as having a shifting pulse, or as a grid that has two rhythms, where the eye jumps over alternating scales as the passage of axial load is interrupted.

If one edge of the square of the structural diagram is extended, and other sides follow in rotation, then a pinwheel configuration is produced. Materialised as pieces of wood that construct the pattern, each strip is placed on top of the previous one. This way, a weave with different convex curvatures emerges.

If the strip of wood is three units long and the small square has a side of one unit, the unit square will be one-fourth the area of the big square. The area relationship of small to big, and the thickness of each piece of wood as it engages the weave, create different curvatures.

If the system of assembly is flipped over (that is, from an arrangement in which each piece is on top of one another to one in which each one is placed below the other), then the curvature reverses to concave.

In emergent design, a grid may turn into patterns of rhythm, framing multiples of squares, as reciprocal bearing structures arrange themselves through space in alternating plan forms. This way the grid becomes not just Cartesian but Emergent; examples can be found in the concepts Balmond developed for the Taichung Opera House (architect: Toyo Ito), the Fractal Wall of the Grand Egyptian Museum (architect: Heneghan Peng) or the Forest Park Pavilion in St Louis (architect: Shigeru Ban) (fig. 6).

Leonardo's reciprocal grid of the roof system in *Codex Atlanticus* can be used as plan for construction of a dome, a sphere, a cylinder, a column or other structures from loose beams. In his drawings, Leonardo was also testing roof systems as domes based on different geometric shapes, such as the triangle. Buckminster Fuller similarly discovered that if a spherical dome structure was created from triangles, it would have unparalleled strength. Triangulation (fig. 7) allows a minimum number of points on a surface to define a shape that can be stable in space and can describe any complex shape or body. This principle directed Buckminster Fuller's studies toward creating a new structural design, the Geodesic dome, based also upon his idea of "doing more with less"; in this way, the largest volume of interior space can be enclosed with the least amount of surface area, thus saving on materials and cost.

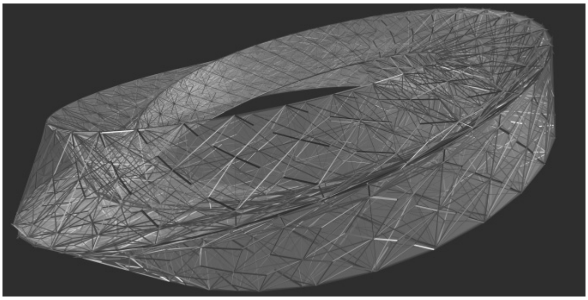


Fig. 7. Structure based on a double Moebius strip with surface triangulation that creates an illusion of depth. Laurent-Paul Robert, Vesna Petresin Robert: Double Moebius Strip Studies, 2002

Buckminster Fuller's geodesic domes, first presented at the 1954 Milan Triennale (entitled "Life Between Artifact and Nature: Design and the Environmental Challenge"), are based on an iterative triangular growing pattern, close to Leonardo's pattern of the roof system. Recurring patterns and spherical geometry allowed Buckminster Fuller to create light, flexible structures such as the 'Tensegrity sphere'.

Tensegrity or "tensional integrity", introduced by Kenneth Snelson, provides the ability of structure to yield increasingly without ultimately breaking. This method of construction is highly efficient and reflects natural generation of structures at cellular levels.

Similar to Leonardo's experiments in frequency and geometry of the roof structure for a dome, Buckminster Fuller's geodesic domes were conceived as fractional (triangular) parts of complete geodesic spheres. A high-frequency dome has more triangular components and is more smoothly curved and sphere-like; but geodesic domes may also be based on other polyhedra, such as the octahedron and tetrahedron. Each of the triangles of the dome subdivision is curved because it is subdivided into smaller triangles, the corners of which are all pushed out to a constant distance from the sphere's centre. This division follows a pattern similar to fractal logic in the growth of space-filling curves or structures that exist between two and three dimensions.

The principle of economy in nature id echoed in modularity. Buckminster Fuller expressed them through his principle of synergetics in a series of prototypes and experimental structures, maps and diagrams.

5.4. Ornament and structure. A sequence of patterns produces ornament that is functionally referred to as decoration. Ornaments can be considered as geometric mandalas and may have structural potential. Leonardo shows that geometric patterns can become blueprints for architectural layouts.

Non-structure-related ornament started disappearing from architecture after Adolf Loos published his 1908 manifesto [1998]. His position was shared by Le Corbusier, who thought decoration was of a sensorial and elementary order, as colour; in his opinion, ornament was suited to simple races, peasants and savages who love to decorate their walls.

But before dismissing ornament as architecturally irrelevant, it should be recalled that Leonardo's drawings reflect the possibility of using its geometric potential to address structural performance in three dimensions. The search for connections at all scales, from microcosmic to macrocosmic, is echoed in his design research, marked by universal principles of geometric, structural and aesthetic equilibrium.

The drawings in *Codex Atlanticus* reveal Leonardo's research in analogies between geometric patterns, their ornamental application and structural potential. His interest in architecture initiated various experiments in engineering and materials. A series of bridge designs were created. Aimed at using minimal profiles, lightweight structure, transportable materials with small profiles and solid, stress-resistant binding elements, these structures were easy to build and, again, followed the interlacing and overlapping principles.

Leonardo uses geometry to achieve stability, order and beauty as he perceived them in the dynamic systems of nature. The dynamics of human perception is reproduced in his structural design. Symmetrical patterns with inherent ambiguity that allow multiple interpretations help Leonardo to adopt universal principles of mechanics, anatomy and bionics.

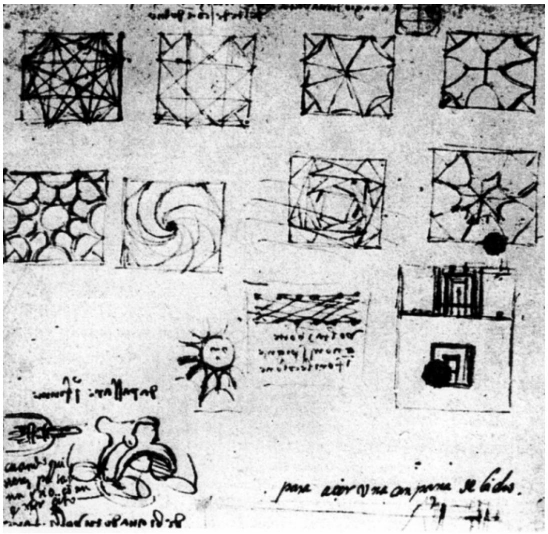


Fig. 8. Leonardo da Vinci, Diagrams of cupolas based on a square plan. MS B fol. 10 v

The evolution of patterns in ornamental design through symmetric transformation (rotation, translation and reflection) is similar to basic operations in architectural morphogenesis. Leonardo applies it to his series of diagrams of cupolas treated as ornaments (fig. 8): he achieves symmetry using the crystallographic principles of translation, rotation and reflection. Translation of an interval produces a rhythmical sequence. In a way, geometric patterns mimic crystalline molecular structure; at a microscopic level, structurally stable shapes also coincide with the elementary geometric shapes indicating visual harmony.

A similar mathematical and crystallographic influence can also be found in the fascinating graphic inventions of Escher, such as in the *Symmetry* watercolour series. Their original inspiration, however, came from his familiarity with psychology and experiments in visual perception. His fascination with order and symmetry seems to have been a later development.

Like Alberti and Leonardo, Escher's inspiration came from the Islamic arts of ceramics, ornamentation, tiling patterns and calligraphy that he discovered at the Alhambra, the abstract geometry and figures merging with each other or the background. He reproduced these principles for a tiling of a surface, using regular plane division as well to create ambiguous structures with perception shifts between figure and background.

Pattern stands for regularity in a particular dimension, that is, repetitive units (motives) ordered by linear (translational) or rotational symmetry. When organised in time, patterns produce rhythm. Repetitive, iterative units indicate a re-use of existing information, producing self-similar structures.

Any organised behaviour can be identified as a pattern within complex natural systems (for example, in physics, biology and chemistry). In art, conceptualisation and construction of patterns in various materials and technologies involves weaving, knitting, printing, matting (as in textiles) rather than basic repetition of motive. These methods can often be found in ornamentation, in graphic as well as architectural design.

Ornaments derived from methods of textile design provided a basis for Leonardo's research of their structural potential: here, again, art and geometry come together. The intriguing research of space-filling patterns to produce the construction grid of an ornament is particularly interesting in Leonardo's drawings of sword heads and ornamentation (fig. 9).

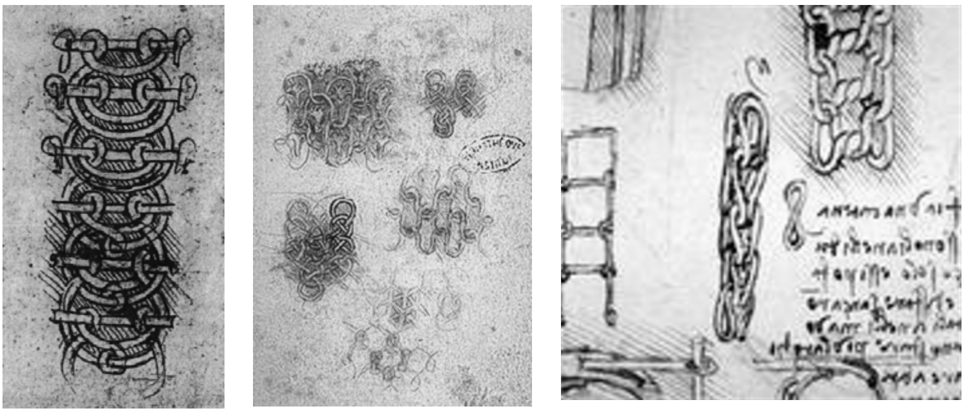
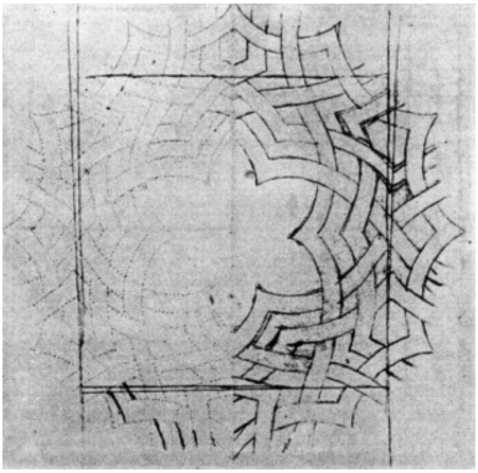


Fig. 9. a, above: Leonardo da Vinci, chain ornament. Codex Atlanticus fol. 681v; b, top right: study of decorative knots and plaiting, Ms. H, H1, c. 33r: c, bottom right: Dismountable chain. Madrid Ms. I fol. 10r (detail)

Periodicity of these compositions is achieved by transformation processes such as translation, rotation and glide reflection, giving a sense of directional movement of the repetitive patterns. Iterative, growing curvilinear patterns mimicking methods in textile design such as interlacing, interweaving and overlapping produce ornament that is analogous to space-filling curves. The drawing technique suggests further ways of development of these ornaments into three-dimensional structures through possible intersections in space.

The iterative growing patterns of 'Academia di Leonardo da Vinci' and *Codex Atlanticus* can be compared to the so-called space-filling curves and monster curves in mathematics. These are generated by iteration, producing a growing configuration that is neither a two-dimensional shape nor a three-dimensional solid. In topological geometry, formations such as a Hilbert curve, knots and the Sierpinski gasket are known to create the ambiguity of evolving from one-manifold (a two-dimensional curve) into two-manifold (a surface) by self-revolving or space-filling pattern growth.

Leonardo's self-revolving, self-similar interlacing ornaments (fig. 10) are close to the notion of fractal dimension (that is, dimension between dimensions) at a very small scale. Emergent aesthetics also offers an analogy to Leonardo's ornamentation in addressing the relations of the whole to its parts: although the whole is seemingly chaotic, an individual part is an ordered, active element generating processes of modifications in time.



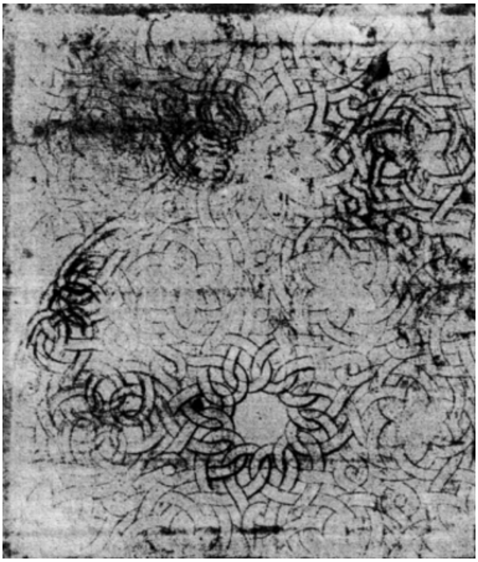


Fig. 10. Leonardo da Vinci, space-filling iterative patterns. *Codex Atlanticus* fol 261ra

Inspired by research in mathematics and physics, especially the spherical concept of the universe, Buckminster Fuller used self-stabilising patterns that are similar to self-similar patterns through which latent order in emergent systems manifests. Form can be retained due to a recurring pattern. Buckminster Fuller therefore defines structure as "locally regenerative pattern integrity" [1975: §606.01]. Such logic of stabilisation and dynamic growth is known in self-similar generation of two-dimensional patterns or three-dimensional structures in a complex system.

Leonardo's attention to details, patterns, geometric ornaments, calligraphy and astronomy is also echoed in the recent research by Cecil Balmond. He explains patterns as building elements of structural networks and as mediators between metaphor and actuality.

The idea that an electronic ornamentation can be created based on computer-generated pattern using the principles of translation, notation and writing, has been developed by dECOi. The lines derived from the rotation of animated forms generate a spatial pattern, as in the electroglyph *Hystera Protera* [1998; Zellner 1999: 69; Goulthorpe 2007: ch. 3]. The computer-generated scriptural sequences are derived from mappings and are referred to as 'glyphics' (to distinguish them from the determinate character of graphics). This fluid, serial, dynamically evolved generative configuration also works as a detail, a structure or a decoration. Electroglyphs are more than a mere multiplication of a series of decorative elements: they can become activated patterns on a responsive surface. In the *Hystera Protera* project, the patterns produce electronic ornamentation that can be generated alternatively by electronic-sensory input or environmental stimuli.

5.5. Ornament as structure and as symbol. The potential of ornament as a structural blueprint and as a semantic entity having symbolic content is fascinating.

An early mythological representation of dynamics found in representations of infinity and eternal revolution is the serpent biting its own tail, such as, for example, the alchemistic ouroboros. Self-revolving patterns and structures were popular, demonstrating an interest in continuous renewal of energy in all manifestations.

Perhaps it is not surprising to find these characteristics in the intertwining spirals of the double helix. The evolving, twisting, dynamic structure of DNA is one of the most stable configurations, based on a generation of an iterative pattern in three-dimensional space. The symbolism of this intertwining, continuously growing structure has also been used as a motive in decorative arts since early times.

In his research in continuous configurations, Leonardo addresses the evolutionary nature of the dual relation between man and universe, between architecture and environment, between outside and inside.

In Pictish and Celtic ornamental art, known to abound in such metaphors, a continuous line was produced using numbers with no common factors with half-sizes at the four corners. Based on methods of textile design such as plaiting, dynamic evolutionary structures, such as knots and spirals, were introduced.

A knot is defined as a curve in space with the ends joined, its two-dimensional diagram showing its crossing points. It is the embedding of one closed curve in three-dimensional space. In mathematics, knots are the subject of investigations of topological geometry along with such self-revolving, continuous phenomena in four-dimensional space as the Klein bottle, Borromean rings and the Moebius strip.

In some of Escher's watercolours, the optical illusion is achieved when the perception of a structure follows a loop. He created a woodcut printed from three blocks in 1963 entitled *Moebius band* that also represents this single infinite surface, always ending up at the starting point, having no beginning and no end.

> An endless ring-shaped band usually has two distinct surfaces, one inside and one outside. Yet on this strip nine red ants crawl after each other and travel the front side as well as the reverse side. Therefore the strip has only one surface [Escher 1992: 12].

In hyperseeing, knots appear to be ideal objects for such a method of viewing, being open rather than solid, with no clear orientation and directional distinction, and appearing different when viewed from various viewpoints.

The structural principles found in knots, plaits and puzzles led Leonardo to design bridges, patterns in wheels, details of wooden structure, chain members, barriers and other devices. He studied the self-revolving as well as growing spirals appearing in vortexes and helical flow diagrams in order to understand principles of rotation, evolution and motion. The drawings in *Codex Atlanticus* (fig. 11) are based on principles of knots – weaving, plaiting, overlapping and twisting – that have been used to create patterns and ornaments. Using transformation processes such as rotation, reflection and translation of a repetitive pattern gives a sense of a directional movement that develops along a curvilinear path. In Leonardo's drawings, such investigations often indicate a possibility of development into structures. Analogies to the organic world are numerous: Leonardo illustrated the principle of ascending spiralling vector that appears in natural phenomena such as vortexes and helical flow in fluids in a series of analytical drawings (fig. 11, above).

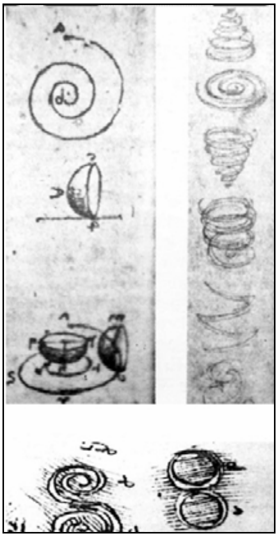


Fig. 11. Leonardo da Vinci. a, left) Studies of knots and spirals. *Codex Atlanticus* fol 292v-a; b, above) Spiral-form mazzocchio formed of two intertwined spiral rings. *Codex Atlanticus* fol. 520r

Similar to Leonardo's drawing of the weaving, twisting ribbons, Escher's woodcut printed from two blocks, entitled *Spirals* (1953), is also an ambiguous self-revolving structure; it has been created using a looping, spiralling structure. Four spiral-shaped bands enclose a twisted tube that revolves to its starting point in a thinning torus-shape; after having completed a tour, the structure makes another tour in a self-revolving way.

In structural design, methods of textile design are used to achieve maximum structural performance of architectural components. Such configurations can adapt to dynamic loads along the three axes of the coordinate system by remaining flexible and elastic. Today, the process of three-dimensional weaving in textile industry is used to create various densities of structural fabric and has been successfully applied to produce resistant structural membranes of great tensile resistance

6 Learning from Leonardo

Leonardo's attempts to conceive a mathematically perfect structure can be compared to the contemporary idea of structural coherence as a way to achieve a dynamic balance. His design is mainly derived from observation of natural behaviours and defies the principles of traditional engineering.

Emergent design similarly relies on the principles of structural growth, efficiency and regeneration found in biological and physical processes. The organic structural principle requires more rather than thicker elements to achieve structural performance. These can be subdivided according to the principle of fractal branching and not in terms of the traditional hierarchy of load-bearing elements. The same thought appears Leonardo's fractal-like subdivision of building components.

Emergent theory has become increasingly important for structural design: emergence is defined as that which is produced by multiple causes but is not directly the sum of its individual effects. Borrowed from biology, mathematics, information theory, artificial intelligence, climatology and bio-mimetic engineering, its key concepts are self-organisation of structures and the hierarchy of bottom-up systems. Such open systems, known from the organic universe, are dynamically imbalanced, constantly in the process of exchange with the context. They adapt by keeping their autonomy, spatial articulation and hierarchies.

Similarly, architecture today is no longer considered an end-product but a process resembling a biological model, constantly optimising according to its environment. Forms and generative patterns are shaped by processes that generate forces of organisation. The principle of adaptation to the environment can be found in Artificial Intelligence systems and smart materials. A dynamic whole or a system of structural patterns is constituted of elements that cannot be interpreted separately from the system. An open, process-based system adapting to the environment, evolving and creating new structures, is the concept common to both the organic world and architecture.

Appreciating Leonardo's notion of the artist who learns from nature, contemporary architecture also investigates geometry of organic shapes to create patterns, ornaments or structures using morphogenetic processes found in genetic algorithms, bio-mimesis and particle physics. The underlying structure of nature is self-similar.

Leonardo's use of geometry in his design concepts is aimed at providing mathematical perfection and structural stability, as well as visual harmony. His architectural concepts reflect an understanding of physical laws, characteristics of materials and self-similarity in organic and built structures, along with a belief in universal principles of mechanics.

The underlying aesthetic order can also double with structural balance. Leonardo must have understood these principles by observation of structures and behaviours in nature. But his interest in concepts rather than construction resulted in a tendency to balance materials and forces in his projects so carefully that any additions to the structure would be unstable; the structure is self-sufficient, with all its elements in precisely defined locations. Such an approach is not far from the tensegrity of Kenneth Snelson and Buckminster Fuller, where every structural member is uniquely located to achieve an integrated optimal performance.

The morphological dynamics of Buckminster Fuller's geodesic domes reveal an ambition similar to Leonardo's: combining structural stability and mathematical perfection with visual harmony. Structure and geometry are interrelated not only in performance, but also in aesthetic requirements.

Evolutionary techniques in architecture involve design principles such as synergetics, tensegrity, organic logic and metaphors in structural design, as well as emergent technologies, to achieve a better structural performance and aesthetic balance (fig. 12). Synergy in design indicates that design concepts involve structural stability as well as flexibility.

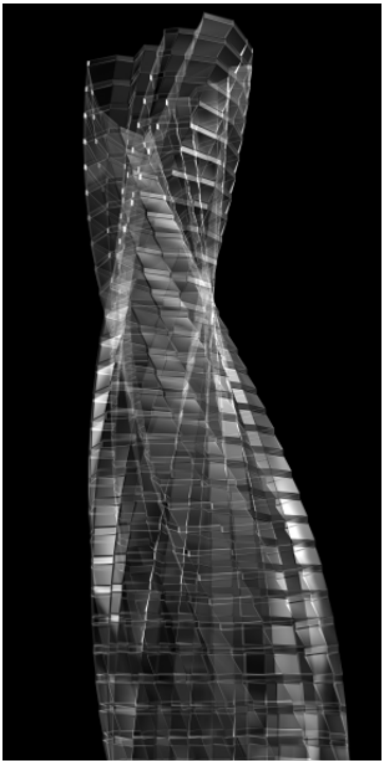


Fig. 12. The basic floor plan shape is derived from the logarithmic spiral. Each iterative step rotates a floor plane and translates it along the *z*-axis. Laurent-Paul Robert and Vesna Petresin Robert: Ophiomorphos, 2002

Synergetics is the principle prevailing in design in imitation of biomorphic structures: tensegrity components require perfect positioning of every single element. The same can be said for both Buckminster Fuller's geodesic domes and Leonardo's carefully calculated structure for the dome. Synergetics is the geometrical coordinate system discovered by Fuller, using the tensegrity principle of interactive relation of parts with the whole. He describes synergy as "the behaviour of whole systems not predictable from the behaviour of separate parts" and the "behaviour of integral, aggregate, whole systems unpredicted by behaviours of any of their components or subassemblies of their components taken separately from the whole" [1979: 101.01-102.00].

Whereas classical and even Modernist architecture polarised ornament and structure, contemporary techniques allow for integration and blurring of inside and outside. A new awareness of surface gives it a role similar to that in biology. In architectural terms, this enables a freedom of expression and form, allowing a diversity of the design addressing patterning and texture, as well as the sensuous and the ornamental.

Leonardo's most important concept in design was the search for analogies between natural and man-made, between aesthetics and functionality. By trying to understand the micro- and macrocosmic harmony, his design successfully resolves not only the issues of ergonomics, but also archetypal human needs – both physiological and psychological – in the built environment.

References

BARBARO, Daniele. 1556. *I Dieci Libri dell'Architettura di Vitruvio Tradutti et Commentati da Mons. Barbaro*. Venice: Francesco Marcolini.

NICHOLAS OF CUSA. 1972. *Nicolai de Cusa Opera Omnia iussu et auctoritate Academiae litterarum heidelbergensis ad codicum fidem edita*. Eds. Josef Koch, Karl Bormann, Hans G. Senger. Hamburg: Felix Meiner Verlag.

*D*ECOI. 1998. *Hystera Protera* Graphic Design / Art Work, Public Art Commissions Agency UK.

ECO, Umberto. 1967. A theory of expositions. *Dot Zero* 4 (Summer 1967).

ESCHER, M. C. 1992. *The Graphic Work.* Köln, Benedikt-Taschen Verlag GmbH.

FRIEDMAN, Nat. 2001. Hyperseeing, Hypersculptures and Space Curves. *VisMath* 3, 1. http://www.mi.sanu.ac.yu/vismath/friedman/index.

FULLER, R. Buckminster. 1975. *Synergetics. Explorations in the Geometry of Thinking*. 2 vols. New York: Macmillan Publishing Co. Inc.

GERM, Tine. 1999. *Nikolaj Kuzanski in renesancna umetnost: ikonoloske studije*. Ljubljana: SKAM.

GHYKA, Matila. 1971. *Philosophie et mystique du nombre*. Paris : Editions Payot.

GIBSON, James J., HAGEN, M A, et al. 1992. Sensory processes and perception. Pp, 224-281 in *A century of psychology as a science*. Eds. S. Koch and D. Leary. Washington DC: American Psychological Association,

GOMBRICH, Ernst. 1979. *Sense of Order. A Study in the Psychology of Decorative Art*. London: Phaidon Press Ltd.

GOULTHORPE, Mark. 2007. *The Possibility of (an) Architecture. Collected Essays by Mark Goulthorpe, dECOi Architects*. London: Routledge / Taylor & Francis

HEMPEL, E. 1953. *Nikolaus von Kues in seinen Beziehungen zur bildenden Kunst*. Berlin: Publisher.

LEONARDO DA VINCI. 1907. Thoughts on Art and Life. *The Burlington Magazine for Connoisseurs* 11, 49 (April 1907).

———. 1956. *Treatise on painting*. Trans. A. P. McMahon. Princeton: Princeton University Press.

LINDBERG, David C. 1976. *Theories of Vision, from Al-Kindi to Kepler*. Chicago and London: The University of Chicago Press.

LOOS, Adolf. 1998. *Ornament and Crime: Selected Essays*. Adolf Opel, ed. Riverside CA: Ariadne Press.

LYNN, Greg. 1998. *Folds, Bodies & Blobs, Collected Essays*. Belgium: La letter vole.

MARTINI, Francesco di Giorgio. 1480-82? *Trattato di architettura civile e militare.* Codex Magliabechiano II.I.141, Biblioteca Nazionale di Firenze.

REISER + UMEMOTO STUDIO. 1998. Tokyo Bay Experiment, Columbia GSAP, New York.

RICHTER J. P. and I. A. RICHTER. 1939. *The Literary Works of Leonardo da Vinci*. London.

STEADMAN, Philip. 1979. *The Evolution of Designs: Biological analogy in architecture and the applied arts*. Cambridge: Cambridge University Press

THOMPSON, D'Arcy. 1993. *On Growth and Form*, J.T. Bonner, ed. Cambridge: Cambridge University Press.

VITRUVIUS, Marcus Pollio. 1960. *Ten Books on Architecture*. New York: Dover Publications Inc.

WITTKOWER, Rudolf. 1988. *Architectural Principles in the Age of Humanism*. New York: St. Martin's Press.
ZELLNER, Peter. 1999. *Hybrid Space. New Forms in Digital Architecture*. London: Thames & Hudson.

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