CRYSTAL OF THINGS POLTAK PANDJAITAN

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POLTAK PANDJAITAN finished his Ph.D. in September 2019 at the Chair of Computer Aided Architectural Design (Prof. Ludger Hovestadt) at the ETH ITA Zurich. His research project *Architectonics of Crystal Space: Mediating and Joining of Spatialities* addressed the question of how to implement and translate spatial concepts in crystal topologies. In 2016 he worked as a project architect for Christian Kerez, for the Incidental Space installation in the Swiss Pavilion at the 15th La Biennale di Architettura Venezia 2016. He worked as an architect at Gramazio Kohler Architects in 2014 and received the TISCHE scholarship from the Federal Chancellery of the Republic of Austria for Arts and Culture in the same year. From 2012 to 2013, he worked as a project architect in Vienna. He studied Architecture at the University of Technology Vienna, where he graduated his Architectural Studies with honours with the diploma thesis *Das verborgene System* in 2011.

Crystals and their specific characteristics dictate the literal pulse in life from the time when quartz crystals were used as oscillating clocks in quartz watches and revolutionized mechanical driven ones. Crystals actually have had a more significant influence on people's daily lives, since the beginning of the information age. The main focus is not the healing effects of brightly coloured berg crystals, but crystals in the form of crystal-line semiconductors. Computers, tablets, smart phones, digital cameras, even the Internet, and all the other things that make communication so much easier these days are all dependent on semiconductor technology.¹

Semiconductors are the built-in transistors, diodes and microchips that led to the information age and contributed to the mobile revolution. These semiconducting materials made it possible to integrate a large number of transistors into a single silicon chip and to place them in a small, universal computer, called smart electronic devices, which we use every day for all our communications and connectivity. Even the basic principle of the semiconductor itself embodies this communication, but on the level of elementary particles. Silicon, which we know in form of silica as sand or in pure composition as quartz crystals, plays an important role for semiconductors.²

COMPOSITION

Crystals as emergent growing structures are interesting, because they have specific properties that are otherwise not found as such in nature. A crystal, despite being so small, is an individual by itself with completely equal properties to those of the large crystal. It is a complete structure, but only to the extent of its internal structure and its external regular form. Its size, however, is not definite: It can always continue to grow as it finds the prerequisites and without changing its nature. In a crystal, the atoms or molecules are arranged in a periodic structure. Each cell is surrounded by neighbouring cells that form an identical pattern. Crystallography is often associated with the study of ideal crystals, where every atom is embedded in a perfectly repeating and ordered structure. But under realistic conditions, you will never find this highly arranged crystal lattice, evenly spread in all directions. Real crystals are configurations of structurabilities, always have some defects in the lattice or impurities in the atomic composition.

- 1 Michel Serres, 'Gnomon: The Beginnings of Geometry in Greece', in *A History of Scientific Thought: Elements of a History of Science*, ed. by Michel Serres (Oxford; Cambridge, Mass: Blackwell, 1995), 73–123.
- 2 Ludger Hovestadt, Vera Bühlmann, and Sebastian Michael, *Genius Planet. Energy Scarcity to Energy Abundance: A Radical Pathway for Creative Professionals and Environmental Active Amateurs*, Applied Virtuality Book Series, 11 (Basel: Birkhäuser, 2017).

In 1982, the world of crystallographic science was confounded by the discovery of a crystal that, although it had a regular structure, was nevertheless globally non-periodic—that is, each cell is surrounded by a different pattern. In terms of crystallography, such a structure possesses a long-range orientational order, but no translational symmetry. Just like a ‘typical’ crystal, these quasicrystals still render sharp diffraction points, but the pattern does not show any crystallographic symmetry. The classical crystallographic restriction theorem indicates that all crystalline structures must have periodically repeating patterns and can only possess two, three, four, and six-fold rotational symmetries.³ A quasicrystal is thereby defined as a structure that has a non-periodic ordering and that lacks translational symmetry.⁴

INTERVAL

The approach to the geometry of crystals or even quasicrystals does not go along with the idea to treat geometry as an accumulation of elements in space. Geometry as a measurement of space is only applied to the projection of the crystal’s algebraic origin. Basic shapes of geometry, such as the triangle, the square and even the beginning of crystallographic thinking, with the platonic solids as definitions of vertices in space, are already renderings of a specific kind. The vertices have been determined in the Euclidean space and do not inherit the information of the abstract as such.

Different from Euclid and his predecessors, to see the open triangle and the resulting diagonal as an enclosed space, the triangle can also be represented as the half of a square with equal legs, or in general as a parallelogram in two-dimensional space. With that in mind, they would probably have treated the nature of the triangle in the vector space. All the incorporated basic ideas, such as the point as a null vector, the segment as a multiplication of a vector with a scalar, the diagonal as the addition of the vectors, the angle of the segments by creating their scalar product and even the aperiodic Fibonacci chain by vector projection with the dot product of vectors with an irrational slope, is embedded in the algebraic nature of the vector space:

The metric diagonal was historically lived as a drama of the irrational and certain death for pure thought: We can think it as what could have been the first step of a higher rationality than Euclid’s, so much more profound that the former pure becomes mixed, impure, poorly analysed. So the drama changes camps: the Greek miracle becomes bad luck or a logical error; the idea

- 3 Walter Steurer and Sofia Deloudi, *Crystallography of Quasicrystals: Concepts, Methods and Structures*, Springer Series in Materials Science, 126 (Heidelberg: Springer, 2009).
- 4 Marjorie Senechal, *Quasicrystals and Geometry* (Cambridge: Cambridge University Press, 1995).

of vector space forces me to forget an entire history, seen from then on as a blindness of clear thought.⁵

The set of all possible unit vectors has the form of a circle in two dimensions, the shape of a spherical surface in three dimensions and the form of a general sphere in higher dimensions. The sum, the linear combination, of the vectors of the formed circle and the sphere are linear dependent and cancel each other out, which results in a zero vector: $a_1v_1 + a_2v_2 + \dots + a_nv_n = 0$. The complete crystal space is thereby at the same moment the non-existence of it, in which the zero vector, 0, is also an element of the vector space: $\sum_{j \in J} a_j v_j = 0$

The n-dimensional vector space is the algebraic encapsulation of any crystal system: $e_1 = (1, 0, \dots, 0)$, $e_2 = (0, 1, 0, \dots, 0)$ to $e_n = (0, 0, \dots, 0, 1)$. The coordinate vectors ($e_1, e_2, \dots, e_n$) build the basis and are represented as a sequence of scalars, which are the components of the vectors. It is a finite or infinite set B of vectors b_i , which spans the whole space and is linear independent. Any linear combination of the basis multiplied by scalars can express any vector and by that it envelopes the entire space: $v = a_1b_{i1} + a_2b_{i2} + \dots + a_nb_{in}$. Linear independence means that each vector is unique and none of the vectors is a result of a combination of the others.

The crystal structure is embedded in the sequence of scalars. Perfect crystals, which are built on a regular periodic structure, are classified by their Bravais lattice. They are groups of the seven possible lattice systems (translational groups) in crystallography: $R = n_1a_1 + n_2a_2 + n_3a_3$. The definition of crystals is based on primitive vectors that span the lattice. With integers n_i and linear independent vectors a_i , in case of three-dimensional crystals, i has the value 1, 2 and 3. The vectors and their unit scalar define the specific crystal system. Since perfect crystals have a regular structure and consist of unit cells placed next to each other, the underlying sequence of scalars is simple and repetitive. In case of any non-periodic crystal and combinations of multiple crystal systems, the sequence becomes more complex and significant. The pattern acts as a code, which in the widest sense resembles a language.⁶

The code is only an abstraction, which acts as a container for the structure's information. It does not describe a specific geometry but is itself geometry. Abstraction makes it possible to depict the topology of a structure without giving any indication of the topographical conditions of a geometry. Nevertheless, conclusions can be drawn about the underlying nature, and by means of that it is possible to recognize different patterns, to compare and even to combine them. It allows for a discourse between different geometries, without neglecting its nature and origin.

- 5 Michel Serres, *Geometry: The Third Book of Foundations*, trans. by Randolph Burks (London: Bloomsbury Academic, an imprint of Bloomsbury Publishing Plc, 2017), 12.
- 6 de Bruijn, N. G.. 'Algebraic theory of Penrose's non-periodic tilings of the plane'. *I. Indagationes Mathematicae (Proceedings)*, 84, 1 (1981), 39–52.

This is not the case when the evaluation is based on the rendering, the specification of a nature. It is possible to abstract the topology from a geometry, but not vice versa.

(...) mathematical language A is anterior to language B in the ordinary diachrony. It is almost always possible to translate A into B; conversely, we cannot go from B into A. Euclidean space can be translated into topological, metric, or vector language; conversely, in the Euclidean repertoire, no term corresponds to 'topological manifold'.⁷

In case of crystals, the topology describes the composition and order within the structure. There is no information about the embedded crystal's shape and geometry. Different crystals can be transferred into one another according to the rules of the topology, but they can still have different geometries. It is not sufficient, therefore, to characterize a crystal only by its topological composition, since even isomorphic graphs, networks which have an identical link pattern, can have different topologies. Just like the graph of the trefoil knot, which has the connection structure of a ring, cannot be topologically converted into a ring without breaking the structure.⁸

Topologically, nodes, as intersections of vectors, have no concrete location in space; they are abstract elements that can be placed anywhere, provided that their pattern scheme remains identical to all other nodes. The process of assigning specific coordinates of our common (Euclidean) three-dimensional space to abstract-mathematical nodes and edges depends on the translation of the code, which in the case of algebraic crystals acts as a geometrical renderer. The sequence of scalars is combined with the vectors and then translated into a particular coordinate system. This process of projection, of higher-dimensional information into a relative subspace, leads to structures of specific crystal lattices in Cartesian space.

FIG 1
shadow projection of
a three-dimensional
dodecahedral quasi-
crystal cluster

7 Serres, *Geometry*, 19.

8 Frank Hoffmann, *Faszination Kristalle und Symmetrie: Einführung in die Kristallographie*, Studienbücher Chemie (Wiesbaden: Springer Spektrum, 2016).

SHADOW

But the projection is only successful at a specific angle. Otherwise it reveals nothing. There is a lot of noise between. The crystal keeps the information hidden and only by putting it under the sun does it reveal the encrypted information. The parallel projection unfolds the crystal code, which is not apparent through the central perspective, in the shadow of the artefact that can be read differently: It keeps the information under its noisy appearance.

As Serres observes, Thales's inversion of the gnomon, the casting shadow of the pyramid in relation to the shadow of a gnomon, gives information about the unmeasurable height of the Pharaonic tomb. By that Thales didn't measure the pyramid. Instead he invented an abstract space, where the shadows are relative and open up a space of comparability. It deals with the proportionality of relations of numbers. With the gnomon, it is possible to see something which is only reachable through the introduction of the sun as the third.

Turning this entire process around, Thales poses and then resolves the inverse problem of the gnomon. Instead of letting the pyramid talk about the Sun, that is, the invariant say the scale of the variable, he asks the Sun to speak about the pyramid, that is to say, asks the changing to say something constantly about what remains.⁹

Even the distinction of crystals and quasicrystals is achieved by relating their shadows' symmetries. The casting of the shadow, however, reveals the quasicrystal's nature only at specific angles. Everything in between is a vivid state of indecisiveness: a flickering which jumps from state to state; a three-dimensional key that incorporates multiple two-dimensional projection patterns. The shadow of a regular crystal can also have various patterns at particular angles, but they only embody repetitive patterns and the transition between the states are more traceable. In principle, the projection does not reveal more information than the structure of the crystal itself. But every quasicrystal casts a different shadow. It is like a fingerprint encapsulated in a three-dimensional structure, where the code is only accessible through the third, the sun. The sun acts as a translator, with the parallel projection being the universal language and shadow on the plane is the translation. But like any translation, the reduction of dimensionality has a price. The projection acts as a renderer of the crystal and the various renderings do not give the insight of the overall structure behind it. Only the movement of the sun's trace in time, in combination with the projection of the shadow, defining the origin and reference of both, unfolds the higher-dimensional nature.

9 Serres, *Geometry*, 116.

And therefore, in order to know and comprehend, in order to see, we must be able to move according to the new dimension, following, in the course of the projection, precisely the direction accompanied by the rays of the sun. Space becomes a set of possible movements.¹⁰

In case of a three-dimensional quasicrystal, the artefact is already a reduction of a higher-dimensional crystal. For example, an icosahedral quasicrystal derives from a six-dimensional space, where the shadows are renderings of spectra.

EXPRESSION

In addition to the fact that different crystal arrangements vary geometrically and in their chemical constitution, their underlying code may even contain different information. By recognizing patterns in the code, regularities and recurring sequences can form single unit crystals, as in case of perfect crystals, or several differently shaped ones, in composed structures. In crystals, which do not possess simple periodicity, these sequences in code do not only describe the units of which the crystal consists, but also provide an insight into sections of larger crystal clusters. These recurring patterns can be perceived as an expression of a language, where the individual elements in the code are like single letters in the alphabet or indices of a finite set. They form single words and several words result in a series, which can form a sentence. But a repetitive arrangement of words does not consequentially inherent any literary expression.

The perfect crystal with a periodic structure can, therefore, be seen as a series of contiguous words. The simplicity in information, which in turn also reflects the stability and robustness of the structure, is the self-referencing composition. Each element describes the entire sequence without defining the beginning nor the end. The structure is unified and any fault in the series can be compensated by the element itself.

Crystals, which consist of several units and therefore have a more complex composition, form simple repeating sentences. This makes it possible to express a specific syntax that depends mainly on the elements. The overall recurring structure is the reflexivity of the cluster of elements, which originates from a circular motion. It is a manifestation through repetitive recitation, characterized by a particular order. The sequences of elements as a common denominator are no longer clearly discriminable, and they can only be defined by the relation among the elements, as the boundaries within the series can shift.

Structures of several units that do not have a repeating periodicity resemble a quasicrystal. Different sections of quasicrystals

¹⁰ Ibid., 118.

epitomize varying crystal clusters, which contain, as a whole, specific information. They depict a system that encodes information into an aperiodic sequence.

In his book, *What is life?* published in 1945, the Austrian physicist Erwin Schrödinger postulated that in order for a molecular system to carry information, it must be regular, but also aperiodic. According to him, irregular amorphous materials are too chaotic to have the practical ability as information carriers, but total regularity diminishes the ability to encrypt complex information. Schrödinger believed that the hereditary material is a molecule that, unlike a regular crystal, does not repeat itself. Its non-periodic nature allows it to encode an almost infinite number of possibilities with a small finite number of atoms. He already talks about an aperiodic crystal, even before the discovery of real quasicrystals:

In physics we have dealt hitherto only with periodic crystals. To a humble physicist's mind, these are very interesting and complicated objects; they constitute one of the most fascinating and complex material structures by which inanimate nature puzzles his wits. Yet, compared with the aperiodic crystal, they are rather plain and dull. (...)

That is the case of the more and more complicated organic molecule in which every atom, and every group of atoms, plays an individual role, not entirely equivalent to that of many others (as is the case in a periodic structure). We might quite properly call that an aperiodic crystal or solid and express our hypothesis by saying: We believe a gene—or perhaps the whole chromosome fiber—to be an aperiodic solid.¹¹

Although the discovery of deoxyribonucleic acid (DNA) as a carrier of hereditary information followed later and the underlying structure is not of a crystalline kind, it has properties predicted by Schrödinger. It is a regular but aperiodic molecule. In case of DNA, Schrödinger's prediction for encoding information as an aperiodic crystal was crucial for the discovery of the DNA's nature. Just as sequences of the four different nucleotides (A, T, G, C) express the DNA information of cells, code sequences in crystals represent the instruction for crystalline growth and development. The DNA helix structure can be understood as a one-dimensional quasicrystal, since the non-periodicness of sequence in code, in the case of DNA with its four bases, resembles that in quasicrystals and never repeats periodically.¹²

11 Erwin Schrödinger, *What Is Life?: The Physical Aspect of the Living Cell with Mind and Matter et Autobiographical Sketches* (Cambridge: Cambridge University Press, 2012 [1944]), 2012, 5, 60.

12 Jacques Monod, *Chance and Necessity; an Essay on the Natural Philosophy of Modern Biology*, trans. A. Wainhouse (New York: Vintage Books, 1972 [1971]).

The aperiodic structure acts as a language and a code. What they both have in common is the meaningfulness in organization. It is as if they deal with permutation and combination of a small finite set of basic units in order to create systems of communication. On the contrary to a written text, however, the sequence of the DNA itself does not inherit any meaning. The DNA is much like a programming language, through which the computation of the code gains in significance.

In the world of quasicrystals, specific sections of the code describe aperiodic crystal clusters. Simple periodic order or complex aperiodicity is embedded in the code and certain segments describe respective properties. The development of this specificity is equivalent to the structure of a narrative: It is a language that makes it possible to articulate and differentiate in crystalline structures. The crystal code can be interpreted differently, and the translation can show various renderings. The way abstract language is translated into geometry varies with the projection. This act of differentiation of geometry allows a universal abstract system to be understood in different bodies.

SHIFT

There is not one crystal space, but the articulation and interrelation of multiple ones: combinations of multiple crystals, where their co-existence and juxtaposition are articulated. The non-locality, which describes the nature of quasicrystals, is coupled with a contingent appearance. Quasicrystal structures are neither stochastic nor deterministic. It is never about being able to define and thereby to freeze a certain quasicrystal state. The implication is to appreciate it as a spectrum of multiple configurations. Through instantiation, the constant flux of shifts become graspable and can serve as a statue of communication.

The crystal as an algebraic language never makes a statement, but only translates and communicates. It acts as a communication channel, a placeholder of information, where there is a table of many crystals. But like any language the single letters are just ciphers, like the many single crystals, and the expression and potential are rendered through the process of crystallization—an abstract analogy that represents the crystallization as an articulation of information. Communicating does not mean to agree with each other, but is a discourse like the gnomon in Thales. It sets up a space of homothesis. Communication is not the linkage of two fixed states or positions, but the interlinking of possibilities.¹⁵

15 Ludger Hovestadt and Vera Bühlmann, *Domesticating Symbols: Metalithikum II* (Basel: Birkhäuser, 2014), 112–177.

GLOSSARY

- **NONPERIODIC (PATTERN)**

The absence of a periodic property in a pattern. In a non-periodic arrangement, it is not possible to generate the pattern only by the translation movement of a periodic patch. It is simply one that is not determined by some non-trivial translation. For example, irrational numbers in the decimal system have an aperiodic decimal fraction evolution, just like in the circle number π . The order of decimal numbers never repeats and goes to infinity.

- **NULL VECTOR**

The null vector is in mathematics a special vector of a vector space, namely the uniquely determined neutral element to the vector addition. In a scalar product space, the null vector is orthogonal to all vectors of space.

- **ORIENTATIONAL ORDER**

It means that groups of atoms or molecules lie in the same direction or on the same plane of reference. The distances between these patterns need not be regular.

- **PERIODIC (PATTERN)**

A pattern is considered periodic if a section or cut out of the pattern recurs at regular intervals. It is the principle for defining the basic structure of crystals.

- **QUASIPERIODIC OR APERIODIC (PATTERN)**

Is a special form of non-periodicity. It is based on the aperiodicity found in quasicrystals, in which the specific forbidden non-crystallographic symmetries are apparent. A tiling is quasiperiodic if a section of any size can be repeated without the pattern as a whole being periodic.

- **SCALAR**

In linear algebra, scalar denotes an element of the body of a vector space that is characterized solely by the specification of a numerical value. The multiplication of a vector with a scalar is called scalar multiplication or scaling and results in the scalar multiple of the vector.

- **TRANSLATION (MOVEMENT)**

It is a movement in which all points of a physical system or fixed bodies, (e.g. periodic pattern) experience the same shift. Any

physical body has in space three degrees of freedom of translation and three degrees of freedom of rotation.

- **UNIT VECTOR**

A unit vector in analytic geometry is a vector of length one.

- **VECTOR PROJECTION**

In geometry, a vector projection is the mapping of a point to a line or plane so that the connecting line between the point and its image is in the direction of the given vector. In linear algebra, this concept is extended to higher-dimensional vector spaces. The orthogonal projection (the vector is in the normal direction of the plane) is then the projection of a vector onto a sub-vector space such that the difference vector of the image and the output vector lies in its orthogonal complement.