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Review Article

Grid Cells in the Brain: The First Principle for Hexagon Emergence

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Abstract

This review article is devoted to a qualitative explanation of the fundamental reason for the formation of hexagonal structures in the system of grid cells in the brain (2014 Nobel Prize in Physiology or Medicine). To achieve this goal, use is made of

a) Richard Feynman's classification of three stages in the study of natural phenomena and, first of all, the most important stage of cognition, associated with the formulation of the "first principle" of the appearance of hexagons.

b) A synergetic approach that allows transferring the results of Hermann Haken for the physical system of Benard cells to the neurophysiological system of grid cells.

c) The achievements of the fluctuation theory of phase transitions, which makes it possible to describe the features of processes near bifurcation (critical) points.

d) The concept of " universality classes " that unite the phenomena of animate and inanimate nature.

Keywords: Grid cells; Hexagons; Feynman classification; Phase transitions; Universality classes

Introduction

Hexagonal structures (hexagons) are widespread in living and inanimate world. As biomedical phenomena, hexagons are observed in a grid cell system in the brain [1,2], in the processes of synaptic transmission of information between neurons [3-11], taking into account the hypothesis of porocytosis [12,13], as well as in the study of a relationship between grid-like cells in adults and genetic risk for Alzheimer's disease [14], in the propagation Leao depression and neurological dysfunctions [15] and, in particular, the migraine phenomenon [16], etc. The significant prevalence of hexagonal structures in vital processes, their features of functioning in norm and pathology, undoubtedly require an explanation and deeper understanding. This review article offers a qualitative description of the phenomenon of the appearance of hexagons in the system of brain grid cells, while the quantitative (physical and mathematical) aspects of their emergence are discussed in detail in [17].

The 2014 Nobel Prize for Discovery of Grid Cells and Hexagonal Structures in the Brain

Exactly fifty years ago in 1971, American and British neurophysiologist John O'Keefe discovered a special type of nerve cells in the field of hippocampus, which were named "place cells" because they allowed the animal (rat) to position itself in space [18]. 34 years later in 2005, Norwegian neurophysiologists M.-B. Moser and E. Moser together with their young colleagues-students T. Hafting, M. Fyhn, and S. Molden made a second surprising discovery, finding another type of cells in the entorhinal cortex of the brain that was an additional component of the rat's brain orientation system [1,2]. These cells were called "grid cells" because they have multiple excitation areas, the geometric position of which had the symmetry of a hexagonal lattice. Together, place cells and grid cells created a virtual coordinate system to determine the spatial position, direction, and speed of movement of the rat. Then it was found that grid-like cells were discovered not only in rats but in other animals and humans [19,20]. It is absolutely fair that the 2014 Nobel Prize in Physiology or Medicine was awarded to John O'Keefe, Edward Moser and May-Britt Moser "for their discoveries of cells that constitute a positioning system in the brain "[21].

The Feynman's Classification of Natural Phenomena

Here, it is proposed to use three stages of cognition of natural phenomena, which Richard Feynman, the 1965 Nobel Prize laureate in physics, described in «The Feynman Lectures on Physics» [22] and which, in honor of their famous author, should be called «The Feynman's Classification of Natural Phenomena». These 3 stages are as follows: The 1st stage is observation and obtaining experimental data. The 2nd stage is an analysis of experimental data and the creation of a theory of observed phenomena. The 3rd stage is the most important and requires the formulation of the basic law or the so-called "first principle" underlying the theory that explains experimental data. To emphasize the 3rd stage of understanding natural processes, Feynman used the following words: "…the real glory of science is that we can find a way of thinking such that the law is evident."

As an example that illustrates the understanding of natural phenomena at the level of all three stages of this classification, Feynman considered the phenomenon of light refraction [22]. The beginning of the 1st stage of these studies related to the works of an ancient Greek scientist Claudius Ptolemy who experimentally established the relationship between the angles of incidence and refraction of light at the air-water interface. At the 2nd stage, the Dutch physicist Snell obtained a theoretical formula connecting these angles. And finally, at the 3rd stage, the French mathematician and lawyer Pierre de Fermat formulated his "Fermat principle of least time", according to which a ray of light chooses such a trajectory between two points, along which movement requires the minimum time.

For most systems in which hexagonal structures are observed, there are no studies in which the authors propose an explanation of hexagons at the level of first principles according to Feynman's classification. To the already mentioned biomedical objects should be added here such objects of inorganic nature as Benard hexagonal cells [23,24], hexagons on the surface of the Salt Lake Uyini in Bolivia [25], a huge hexagon in Saturn's atmosphere around its North Pole [26], etc. At the same time, there are two systems, the description of the hexagonal structures in which is very close, in the author's opinion, to the 3rd most important stage of Feynman's classification.

These Objects are Synergistically Similar, But Seemingly Completely Different in Nature:

a) The neurophysiological system of grid cells in the brain and

b) The physical system of Benard cells.

The formulation of the first principle of the hexagon emergence in these systems requires the use of rather complex ideas and results of theoretical physics. The author will try to present these results not on a quantitative, but on a qualitative level, while maintaining, if possible, the scientific rigor of the presentation.

Phase Transitions, Synergetic Approach, Universality Classes

The research of phase transitions and critical phenomena is an essential part of the study of nonlinear systems in which, under certain conditions, the formation of ordered structures occurs.

The Fluctuation Theory of Phase Transitions Uses the Following Main Concepts [27-36]:

a) Order parameter is the main quantity characterizing the spontaneous breaking of the symmetry of the system at bifurcation (critical) points (see examples of order parameters below).

b) Fluctuations are random deviations of any quantity from its mean value.

c) Correlation radius (or correlation length) is the distance at which fluctuations of the order parameter have a strong mutual influence.

d) Phase transition is a process with spontaneous breaking of the previously existing symmetry of the system and the appearance of a new symmetry as a result of the interaction of fluctuations of the order parameter.

The concept of a phase transition, which previously referred mainly to physical systems, organically entered other fields of science and technology, became necessary for solving problems of chemistry and biology, medicine and ecology, sociology and politics, etc. It is the universality and general features of systems near bifurcation (critical) points, at which phase transitions occur, that makes it possible to apply unified scientific approaches to them. This makes the use of the physics of phase transitions and critical phenomena one of the most fundamental methods for studying the features of the processes of changing objects of animate and inanimate nature. The development of the theory of phase transitions was of primary importance for the creation of synergetics and its effective methods.

Synergetics is an Interdisciplinary Science Integrating Similar Phenomena in Systems of Different Nature that are:

a) Open, i.e. exchange with the environment by energy, matter and information.

b) Non-equilibrium i.e. characterize by processes changing in time and space.

c) Nonlinear, i.e. have feedback between the variables describing their state.

d) Complex, i.e. consist of a large number of interacting subsystems [37-40].

The synergetic approach demonstrates its effectiveness due to the possibility of transferring the results of one science (e.g. physics), being simpler and more precise, to objects of another science (e.g. neurophysiology), being significantly more complicated, less precise and which can be described on a qualitative rather than quantitative level (see e.g. [39,40]). Below, based on the synergetic approach, the results obtained by Hermann Haken [37,38] to explain the appearance of Benard hexagonal cells will be used to formulate the first principle underlying the grid-cells emergence in the brain.

The Concept of Universality Classes is Fundamental to the Consistent Application of the Fluctuation Theory of Phase Transitions to Such Phenomena of Animate and Inanimate Nature as Follows:

a) The formation of hexagonal structures in the form of Benard cells as a result of convective instability in a viscous fluid with a temperature gradient at the critical Rayleigh number [24].

b) The appropriate transfer of these results based on a synergetic approach to the system of grid cells in the brain.

According to the concept of universality classes, basic conditions of the similar behavior for bulk systems of different nature near the bifurcation points or points of phase transitions should be the following:

a) The same dimension *d* (*d* = 3 for all bulk systems, *d* = 2 for all finite-size systems in one direction like monomolecular films, *d* = 1 for all limited systems in two directions like monomolecular thread).

b) The same dimension (number of components) *n* of order parameter where $n = 1, 2, 3$

c) The same type of the radius of intermolecular interaction (short- or long-range).

d) The same symmetry of the fluctuation part of thermodynamical potential (or the so-called Ginzburg-Landau Hamiltonian) [27-34]. The universal behavior for bounded systems needs several additional conditions [30,34-36].

The First Principle for Hexagon Formation in Grid-Cell System

To explain the appearance of grid cells in the brain, Edward Moser, the 2014 Nobel laureate in physiology or medicine, who also studied mathematics, statistics and programming at University of Oslo, suggested in the Nobel lecture [21] to use the analogy between the grid cell system and vortex structures in superconductors of the 2nd type discovered by Alexei Abrikosov, the 2003 Nobel laureate in physics [41]. It is known that superconductors are substances in which, under certain conditions, there is no electrical resistance and heat losses during the flow of an electric current. The essence of the theoretical discovery of Abrikosov, which was first predicted experimentally by Lev Shubnikov and his co-authors [42] and subsequently received direct experimental confirmation by U. Essmann and H. Trauble [43], is as follows. Unlike superconductors of the 1st type, experimentally discovered in 1911 by Heike Kamerlingh Onnes, the 1913 Nobel laureate in physics, and theoretically investigated by Vitaliy Ginzburg and Lev Landau, both Nobel laureates in physics [44], superconductors of the 2nd type can transmit a magnetic field into themselves in the form of filamentous formations called «Abrikosov vortices.» In the inner region of the Abrikosov vortices, the substance is in a normal, not superconducting state. Under certain conditions, electric currents can be passed through superconductors of the the 2nd type, the density of which reaches enormous values. With an increase in the magnetic field, repulsive forces arise between the Abrikosov vortices, and they form periodic structures that have the symmetry of a triangular lattice. Of course, only admiration is caused by the fact that neurophysiologists Edward and May-Britt Moser suggested that the formation of hexagons in grid cells may be associated with fluctuation effects in the physical system of superconductors, where phase transitions occur.

The idea of this review article is to use not only the main results of the physics of phase transitions, but also an additional application of the synergetic approach to transfer the theoretical results of the study of the physical system of Benard cells to the neurophysiological system of grid cells to formulate the universal first principle explaining the appearance of hexagonal structures in various objects of living and inanimate nature. In the author's opinion, the proposed idea is more attractive than the idea of the similarity of hexagonal structures in a grid cell system and repulsive interactions of the Abrikosov vortices in superconductors in magnetic field.

To Implement the Proposed Program, a Few Fundamental Remarks Should be Made

a) 1. Both systems of grid and Benard cells considered here belong to the same class of universality called "The 3-dimensional Ising model with a scalar order parameter and a short-range interaction radius". In particular, the system of grid cells in the brain is synergetically similar (isomorphic) to a system with chemical (biochemical) reactions, the order parameter of which is a scalar quantity with n = 1 and is called the degree of completeness (reaction coordinate). It should be noted that the degree of completeness of a chemically reacting system and the associated value of the affinity of a chemical reaction were introduced by Theophile de Donder [45]. The system of Benard cells, which is isomorphic to a one-component liquid with a short-range interaction, for which the scalar order parameter with n = 1, being the local density deviation from its critical value.

b) For the theoretical description of Benard cells, Hermann Haken used the generalized Ginzburg-Landau equations for the order parameter [37,38]. As a result of the numerical solution of these equations, as previously established by Greenside, Cochrane Jr. and Schraer (see [38]), it turned out that hexagons are not detected in the absence of a term proportional to the square of the order parameter in these nonlinear equations. At the same time, Haken showed in his unpublished studies that in the presence of such a term, numerical calculations lead to the appearance of Benard hexagonal cells.

c) Here, to explain the presence of a quadratic term in nonlinear equations for the order parameter, the hypothesis of conformal invariance by Alexander Polyakov [45] was used, which consistently takes into account the symmetry of the fluctuation part of thermodynamic potential (the Ginzburg-Landau Hamiltonian) in liquid systems (see physical and mathematical details in [17]).

d) Taking into account the synergetic similarity (isomorphism) of the system of grid cells in the brain and the system with chemical (biochemical) reactions, a fluctuation model for studying the formation of ordered structures (hexagons) is proposed in [17]. This model uses the fluctuation part of the Gibbs free energy in the form of the Ginzburg-Landau Hamiltonian, which, based on the hypothesis of Polyakov's conformal invariance, contains a term that is odd (cubic) in the order parameter of the system of grid cells, which is the degree of completeness (coordinate) of the reaction. Accordingly, the nonlinear kinetic equation for the order parameter includes a quadratic term, which, as in the case of Benard cells, ensures the appearance of hexagons for a system of grid cells in the brain.

Conclusion

The main idea of our approach is the synergetic similarity of the processes of formation of hexagonal structures near bifurcation (critical) points in various systems of animate and inanimate nature. This idea allows one to transfer the rigorous theoretical results obtained for a relatively "simple" physical system of Benard cells near the state of hydrodynamic instability to a much more complex neurophysiological system of grid cells in the brains of humans and animals. A fluctuational model was proposed that considers the formation of hexagonal grid cells as a structural phase transition caused by nonlinear interaction of fluctuations of the order parameter of chemical reactions. In accordance with the Feynman classification, on the basis of such a fluctuation model, which takes into account the main consequences of the phase-transition theory, the first principle of the formation of hexagons in the system of grid cells in the brain of humans and animals was proposed. The essence of this principle can be formulated as "the synergetic first principle of the formation of hexagonal structures due to the nonlinear interaction of fluctuations of the order parameter in animate and inanimate nature."

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