



Research Signpost  
37/661 (2), Fort P.O.  
Trivandrum-695 023  
Kerala, India

D. Fels, M. Cifra and F. Scholkmann (Editors), *Fields of the Cell*, 2015, ISBN: 978-81-308-0544-3, p. 271–282.

# Chapter 14

## Morphogenetic fields: History and relations to other concepts

Lev V. Belousov

*Laboratory of Developmental Biophysics, Faculty of Biology, Lomonosov Moscow State University*

**Abstract.** The notion of field was introduced in biology by Alexander Gurwitsch 100 years ago. Since then the “field approach” passed a tortuous way, met a strong opposition and has been used in different meanings. We review its history and discuss the relations between this approach and the more modern theory of self-organization, as well as the possible physical foundations of the field notion, as applied to biology.

Correspondence/Reprint request: Dr. Lev V. Belousov, Laboratory of Developmental Biophysics, Faculty of Biology, Lomonosov Moscow State University. E-mail: morphogenesis@yandex.ru

### 1. Gurwitsch’s field constructions

The notion of a “field” (under the term Kraftfeld, a field of force (or forces) was introduced into biology by Alexander Gurwitsch (1874-1954) (AG) exactly one hundred years ago (Gurwitsch, 1912). From the very beginning and until now it has been most closely linked with a fundamental problem of morphogenesis, that is, the formation of new space-temporal structures during the development of organisms. Although a real physico-chemical nature of the forces involved in structural formation became elucidated step-by-step only in our days, it was obvious already at the time of first AG publications that such forces, whatever be their origin, are highly ordered both in space and time. Moreover, it had already been discovered that embryonic development obeys quite peculiar holistic laws, looking incompatible with the principles of inorganic sciences of those times. This discovery was made in 1891 by the German embryologist Hans Driesch (Driesch, 1891; see also Mocek, 1974) who demonstrated that at the early developmental stages a

well-structured whole organism can develop from just a part of embryonic material. Driesch's results undermined so called preformism, a wide spread believing that a complicated structure of an adult's body correlates in one-to-one manner to a similarly complicated structure of an egg. A failure of preformism meant that a "whole" possesses the formative capacities irreducible to any more elementary mechanisms. By introducing the notion of a "Kraftfeld", AG tried to pave a way for a rational solution of this mystery.

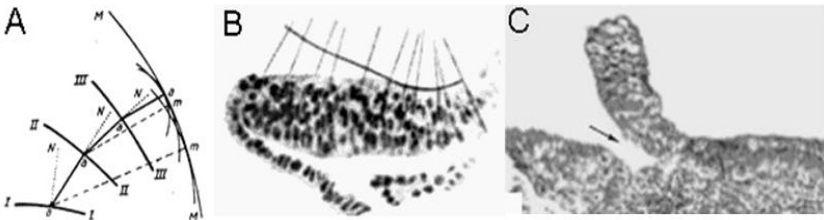
Meanwhile, the title of his above mentioned paper from 1912, "Vererbung als Verwirklichungsvorgang" (engl.: Heredity as a process of realization) reflected the author's reaction to the first steps of a newly born science, genetics. Welcoming its quantitative approaches, AG was at the same time disappointed by its focusing onto the problem of transmission of hereditary factors, neglecting at the same time the very process of realization of genetic information during development. This marked the beginning of a prolonged opposition of the field approach and that of a corpuscular genetics – an opposition which only recently became to be transformed into a more tolerant and even fruitful cooperation.

The first field constructions were associated with the notion of a so-called "dynamically preformed morpha" (DPM), with the following description. By analyzing the morphogenetic movements of large cell collectives during formation of the different organs AG concluded that within a substantial period of development the cells are moving and reoriented as if being attracted by some unknown force, whose location coincided with the final shape of a given rudiment, not yet achieved at the given moment of development. This "prospective" shape was called DPM because before the end of development it existed only dynamically, rather than materially (like an equipotential surface of a physical field). Accordingly, the "field of forces" was defined as a territory onto which DPM extended its action. Most important, it was suggested that the field action should be described by a simple mathematic law (to be established experimentally), retaining its invariability within a large enough time period. Thus, the DPM concept was directed towards endowing Driesch's holistic factor by measurable dynamic properties. In his next work on embryonic brain formation (Gurwitsch, 1914) firstly described a remarkable property of the so-called "prognostic" cell orientation: the radial cell axes of embryonic epithelia were oriented perpendicularly to as yet non-existing final shape of epithelia (that is, to DPM) which by the author's idea had a capacity to rotate and reorient cell axes (Fig. 1A, B).

The same concept was employed somewhat later for interpreting shape formation of some plant and fungi rudiments (Gurwitsch, 1922). Now the term "field" was for the first time included into the paper's title, which stimulated a rapid burst of popularity of the entire concept. However, AG

himself soon put the DPM concept aside for two main reasons. First, he was unsatisfied by its poor capacities for generalization: the DPM concept should be taken ad hoc for each next object and period of development. Second, it was inapplicable to molecular level events, which AG met with increasing interest.

Meanwhile, in the context of contemporary science, the DPM concept still keeps some interesting properties. First, from the viewpoint of a modern systems theory it should be regarded as a first model belonging to the category of so-called target-oriented models (Teufel, 2011). More concretely, it can be precisely reformulated in the terms of the fields of mechanical stresses which seem to play a primary role in morphogenesis (Belousov, 1998, 2008b). More specifically, DPM can be identified with a surface of minimal mechanical energy to which a mechanically stressed cell layer tends to approach gradually in the course of normal morphogenesis and rapidly jumps when the stresses are experimentally relaxed (Fig. 1C).



**Figure 1.** A concept of DPM (A, B) and its modern interpretation (C). A: DPM coincides with as yet non-achieved final rudiment's contour MM, which has a capacity to set up the cells axes at the preceded developmental stages (contours I – I, II – II, III – III) along the bisectors between the directions normal to momentary layer's surfaces ( $aN$ ) and those perpendicular to DPM ( $am$ ). B: cross-section of a part of an early neurula stage fish (*Selachia*) embryo. Solid curved line is DPM and straight lines the axes of cell nuclei which are perpendicular to DPM. C: Same stage cell layer of a frog embryo jumps towards the DPM configuration immediately after its detachment from the underlain tissues (arrow) indicating that the DPM position corresponds to the maximally relaxed state of the beforehand mechanically stressed embryonic tissue (A, B from Gurwitsch, 1914; C from Belousov, 2008a).

Anyway, in early 1940's (just during dramatic events of World War II: see Belousov, 2008a) AG extensively reformulated his field concept by suggesting that a field of a whole is summed up from the "elementary cell fields" (Gurwitsch, 1944; posthumous publication: Gurwitsch, 1991).

The main principles of the new version were the following:

*“The field acts on molecules. It creates and supports in living systems a specific molecular orderliness. This means [...] any spatial arrangement of the molecules which cannot be derived from their chemical structures, or from equilibrium states such as chemical bonds, van der Waals forces, etc. Consequently, molecular orderliness generally is a non-equilibrium phenomenon [...]. The field is anisotropic [...] continuous and successive [...]. During cell division the cell field divides as well [...].*

*A cell creates a field around itself; that is to say, the field extends outside the cell into extracellular space [...]. Therefore, at any point of within a group of cells there exists a single field being constituted of all the individual cell fields [...]. Hence, the properties of this common field will depend, besides other factors, also on the configuration of the multicellular whole. Rather than postulating independently existing supracellular fields, we now attribute their function to a field representing the vectorial addition of the individual cell fields [...].*

*A field is somehow associated with the molecules of chromatin, but only while they are chemically active [...]. A postulated field continuity may be understood molecularly in the following way: if in the vicinity of chromatin molecule A, which is at the given moment a field “carrier”, an active chromatin molecule B is synthesized, the field of molecule A induces the field of molecule B losing at the same time its own field [...].*

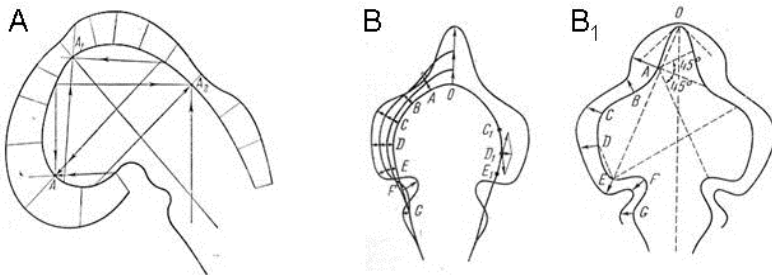
*The field employs the energy released during exothermic chemical reactions in living systems to endow molecules (proteins, peptides, etc.) with ordered, directed movement... A point source of a cell field coincides with the center of the nucleus; hence, the field is, in general, a radial one... The direction of the field vectors is centrifugal (i.e. the vectors are directed from a field center to the periphery)” (excerpted from Gurwitsch, 1944).*

As seen from this excerpt, in spite of extensive reformulation of the entire concept, the new version of the field concept remained to be a system of directed forces, although now deriving the required energy from the local metabolic processes, rather than from the field sources which may be external to the affected staff. This should be estimated as a remarkable preview of the notion of an “active medium” employed in the modern self-organization theory (SOT) (see, e.g. Krinsky and Zhabotinsky, 1981).

Meanwhile in Russia, soon after AG’s publication (Gurwitsch, 1944), a small team of DPM admirers was very much disappointed by the new field concept; in their opinion, it destroyed the very idea of an irreducible “whole”. Gurwitsch (1947) rejected these reproaches by arguing that the central role in his new concept was played by a holistic geometry of cell layers, non-separable to its elementary components. The main advantage of the new version was a possibility to derive each new and more complicated embryonic shape from a preceding, less complex one. This was the first attempt to

formulate what is called today the generative laws of shape formation (Goodwin, 1994). The first applications of the 1944 theory to such a task were promising (Fig. 2). It took some time to recognize that the success of the “form out of a form” idea did not verify just this field construction; the observed shapes successions could be explained in another way, better correlated with empirical data (Belousov and Grabovsky, 2003).

Today we have to conclude that in spite of several insights, this second field concept from 1944 is incompatible with subsequently discovered mechanisms of cell movements and interactions. For example, according to the 1944 concept only the repulsive cells interactions are implied, while during most important morphogenetic movements (so called latero-medial cell convergence (Shih and Keller, 1992) large amounts of cells are moving towards each other. Moreover, with the exception of few cases of negative chemotaxis (Gilbert, 2010) no distant cell-cell interactions passing via cell free space have been ever observed. (It is worth mentioning in this respect, that the explanatory principles of the routine chemotaxis models and the field models are quite different: while the first refer to quite local (point-like) factors of embryonic cells activities, the second ones are dealing with collective (as a rule, delocalized) factors. From a more general point of view, the local factors can be considered as a particular (degenerated) case of delocalized ones, but not vice versa).



**Figure 2.** Deriving “form out of form” on the basis of the 1944 year version of Gurwitsch’s field theory. A: three brain vesicles shape (the outer contour) is derived from a preceded one (the inner contour). (From Gurwitsch, 1944). B, B<sub>1</sub>: a similar construction for the morphogenesis of a hydroid polyp Obelia. B: its final shape (outer contour) derived from less differentiated one (inner contour) under assumption of the field interactions between the neighboring cells only. B<sub>1</sub>: same construction adjusted by adding long-range interactions (dashed lines) (from Belousov, 1968).

In any case, we have to accept that the main advantage of the 1944 field concept was in formulating (rather than solving) a challenged task of deriving a macroscopic type of behavior with systems-level properties from the rules describing the behavior of the systems subunits (see Levin, 2012). As learned by the history of science, to formulate a new task is much more important than to suggest its particular solution.

## 2. A field concept as viewed in modern developmental biology

As briefly mentioned before, the field theory was rather popular in developmental biology of the third decade of the 20<sup>th</sup> century. Besides the influence of Gurwitsch's papers, this was caused by several outstanding discoveries which may be adequately illustrated by the following experiments (Harrison, 1918). A rudiment of a limb in Urodela embryos, well before it takes a visible morphology, can produce a normal single limb:

1. after its transplantation to abnormal location;
2. after its fusion with another similar rudiment;
3. out of its small part;
4. after the mutual replacement of its constituent parts.

Besides, by inverting the limb rudiment at the different developmental stages in relation to antero-posterior (AP) and/or dorso-ventral (DV) embryo polarity it was established that at the earliest stage neither AP, nor DV limb axes has been firmly fixed: after rotations both of them have been adjusted according to the host polarity. Somewhat later the AP, and not DV limb axis became firmly fixed, the latter one becoming fixed even later.

These results are directly related to the field concept because they show that the process of determination is essentially holistic: a period of development can be outlined when none of the minor rudiment elements (single cells, or small cell groups) as yet selected their final fates, while the elements related to the upper wholes (the entire rudiment or its axes) already did so.

Accordingly, at that time embryologists put in the center of a field theory a notion of an embryonic territory endowed by holistic properties. At the earliest stages, as shown by above mentioned Driesch experiments, such a territory coincided with that of an entire embryonic body, while later on a common field became segregated into a number of more local ones. The best formulation of such kind of fields was given by Brian Goodwin (personal communication): "A field is a domain of a relational order". It is indeed a territory where all the cells perceive somehow each other and in the case of any external interventions are ready to change their presumptive fates for restoring the whole. Noteworthy, Goodwin's definition is applicable also to

the last version of Gurwitsch's field. Meanwhile, non-Gurwitsch's fields did not imply any dynamic factors and were purely descriptive. This kind of field concept was elaborated most extensively by Paul Weiss (1939).

Even in such a reduced form the field concepts have been numerous attacked by representatives of a "materialistic majority" which believed that everything related to development should be explained in terms of molecules. One can distinguish two groups of such attacks. The first one came from a discovery of a chemical nature of so-called Spemann's organizers (now usually defined as inductors) (Gilbert, 2010) that is the factors generating complicated patterns of so called axial organs out of unprepared embryonic tissue. The second came from the traditional opponents of the field theory, the genetics, whose mostly fierce adherents believed that everything within the organisms can be reduced to the action of mutually independent miniature corpuscular factors (Gilbert et al., 1996). Closer to our time both trends to a large extent merged together because the action of inductors has been interpreted in the terms of cascades of genes activation.

True, the most insightful representatives of both camps had already understood long ago that neither the action of "organizers" nor the genetic effects disprove the field idea; rather, they indirectly confirmed it, although in a modified form (Waddington, 1940; Rapoport, 1996). For example, it was observed, that most of mutations spread their effects over definite territories, coinciding with those described beforehand by embryologists as the fields of organs. In other words, the organ-forming territories react to genetic mutation as holistic systems, rather than the mosaics of independent parts. So called homeotic mutations (Lewis, 1978), exchanging in the same location one organ to another (for example, an insect leg to antenna) also acted as the switchers between two discrete "wholes", instead of affecting embryonic tissue in a mosaic way. These and other related facts brought the influential modern authors to the important conclusion that "the morphogenetic field (and not the genes or the cells) is seen as a major unit of ontogeny whose changes bring about changes in evolution" (Gilbert et al., 1996). Meanwhile, such a marriage of two harsh former opponents, the fields and the genes, led unavoidably to substantial modifications of the beforehand formulated field concepts. First, it became obvious that the action of genetic factors upon fields should be somehow introduced into the field theory. Second, the modern studies on the inductive interactions between embryonic tissues have shown that already a non-induced tissue is quite far from being a tabula rasa, containing instead in some potential form a restricted number of discrete potential pathways, each one of a holistic nature. This extensively enriches a field concept, bringing it closer to the deep Bohm's ideas of an implicit and explicit order (Bohm, 1980). The first category of order is not enfolded in Euclidean space, while the second one is. By Bohm's idea, the first one is more fundamental.

At approximately the same time, a popular concept of “positional information” (PI) appeared (Wolpert, 1969, 1996) and has been regarded by many as a substitute of field concepts. It is not so, however. The PI-concept postulates the existence of some number of independent PI “sources” and “sinks”, dictating the course of development to all the other, “passive” elements of embryo. No laws of PI have been ever proposed; every next PI action is taken ad hoc. More concrete, PI concept can be shown to be incompatible with the basic phenomena of embryonic regulations (for details see Belousov, 1998).

### 3. Field concept and a theory of self-organization

The reasons for introducing the field concept in biology were quite different from those motivating the physicists to formulate a theory of electromagnetic or gravitational fields. While in physics the notion of field was used for describing a long range action of a signal emitted from a definite source and then passively transmitted through an “empty space”, in biology from the very beginning this notion was used for comprehending the origin of a complicated organization from something less (or even non-) organized; contrary to physics, the “action at a distance” was not an indispensable component of a biological field. Being confronted with the problem of a spontaneous (non-imprinted from outside) complication, the XIX century end biologists unexpectedly and non-deliberately turned out to be very much ahead of the contemporary physics, though still adhered to the principles of linear (one-to-one) determinism. Interestingly, the latter’s principles have been reformulated in the terms of a symmetry theory (Curie, 1894) almost simultaneously with the publication of the beforehand mentioned Driesch experiments (year 1891). It is thus understandable why Driesch considered his results as incompatible with the laws of inorganic sciences.

However, at this time the first milestones were being laid by Henry Poincare (1893) and Alexander Lyapunov (see Prigogine, 1980) to the basis of what was called much later “a non-linear way of thinking”. More than half a century was passed before it was realized that these treatises, being at the first glance quite far from biology (they were related initially to celestial mechanics), created a basis for a new world view, permitting to regard self-complication as an inherent property of a large class of systems, both organic and non-organic. Closer to our time, this approach was defined as a self-organization theory (SOT) (Nicolis and Prigogine, 1977) or synergetics (Haken, 1978). Within a SOT framework, Driesch’s embryonic regulations and the top-down causation could be considered as widely spread natural events, rather than specific properties of living beings only.

Remarkably, some basic ideas of SOT were formulated by biologists in a close context to the field theories even before SOT itself took a modern co-



herent shape. This was done by Waddington (1940) who introduced the notion of chreodes, precisely translated into SOT language as the structurally stable developmental pathways. Few decades later Thom (1970) defined the morphogenetic field as a region of a phase space surrounding a chreod and giving rise to a definite morphology.

Implications from SOT very much affected the content and the status of the field concept(s) in biology. So far as the crucial problem of morphogenesis – to explain a self-complication of organic shapes during development – can be at least in principle solved within a SOT framework, the “biological fields” lost the positions of new first principles becoming instead the derivatives of such fundamental SOT notions like non-linear feedbacks and parametric regulation. In a broad sense, any concept using these notions can be considered as a step towards field constructions (e.g., Chialvo, 2010). It is also worth mentioning that the self-organizing fields well may be defined within a phase space of any developmentally important variables, rather than within 3D Euclidean space only, as took place in the classical fields.

#### **4. Perspectives of the field approach in biology and its physical foundations**

Although the “field approach” in biology is not generally acknowledged, its importance is today much better recognized than it was in the recent past and its usage, even if in rather vague terms, is extensively increased. It becomes ever more clear that this approach is the only one giving hope to overcome a routine view to the prolonged successions of complicated space-temporal events (creating the very essence of the biological processes) as something given ad hoc and inaccessible to the rational explanation. As discussed elsewhere in more details (Belousov, 2011), natural sciences know two alternative rational approaches for explaining such successions: either to postulate that they are based upon unique chains of highly specific cause-effect relations or that they obey some general nonspecific embracing invariable laws. Physical sciences, since Galileo and Newton times definitely took the second approach: when tracing the successive positions A, B, C... of a thrown stone, we look for a non-specific law embracing all of them (and potentially any others), rather than postulating the existence of different specific forces bringing a stone from A to B, then from B to C, etc. In biology, for several historic reasons for a long time the alternative ideology dominated. However, hope to discover a specific one-to-one cause-effect relation for each next step of the biological successions failed: with the refinement of experimental techniques the ambiguity of cause-effect relations (e.g., the relations between genetic or epigenetic factors on one hand and the resulted morphology on the other) increased rather than diminished. Therefore, in biology, as

well as in the physical sciences, for reaching a rational explanation we have no other choice, than to use a law-centered approach, exemplified by a field theory. Remarkably, in spite of having at the times of its origin an obvious vitalistic flavor, this theory is now bringing biology closer to a cognitive basis of non-biological sciences.

What might be, in this context, the physical foundations of the “biological” fields? Although AG did not identify his “embryonic” or “cell” fields with any one known in physics, he was not sure that his concept requires the introduction in the science of some new first principles. In one of his last papers he suggested that “the idea of a field can be probably in some future expressed in physical language” (Gurwitsch, 1947).

Since then, some important steps in this direction have been made. Most important ones are associated with the notion of the “protein-machines” (McClair, 1971; Bluemenfeld, 1983), the molecular devices transforming non-vectorized chemical energy to a vectorized mechanical one. This function is almost identical to that ascribed by AG to the cell fields in his 1944 year version (see above). The main common feature of all the protein-machines is a considerable retardation of relaxation rate of the accumulated energy and enormous restriction (often up to one) in the numbers of freedom degrees onto which the relaxation is taking place. In addition to these short-range molecular devices, another kind of supramolecular devices, so called low entropy machines associated with extended domains of ordered water have been recently postulated (Del Guidice et al., 2005).

Both kinds of machines can be regarded as something like elementary “bricks” of the fields. It remains unsolved however how their action is effectively integrated (rather than dissipated) on much larger scales, typical for multicellular organisms. This difficulty may be at least partly surmounted by taking into consideration a universal physical factor, acting on quite different scales and able to spread its action throughout large tissue regions: the mechanical stresses. As speculated elsewhere (Belousov, 2008a), the macroscopic and structurally stable fields can be established by the interplay of the passive (coming from outside of a given embryo part) and the active (generated within a given part) mechanical stresses.

Another physical factor, somehow associated with the fields, is the ultraweak photon emission from the living tissues (Popp et al. eds., 1992). This factor is also extensively delocalized and creates regular temporal patterns, linked with physiological functions of cells. Some experiments indicate its mechanosensitivity (Belousov, 2006). However, at the present time we are still far from creating a coherent concept of a “biological” or, in a more restricted sense, “morphogenetic” field. This will be a challenging task for the next generation of investigators.

## References

- Belousov, L.V. 1968. Interpretation of a succession of morphogenetic processes in a hydroid, *Obelia*. Biol. Nauki 7: 21–27 (in Russian).
- Belousov, L.V. and additional commentary by J.M. Opitz and S.F. Gilbert. 1997. Life of Alexander G. Gurwitsch and his relevant contribution to the theory of morphogenetic fields. Int. J. Dev. Biol. 41: 771–779.
- Belousov, L.V. 1998. The Dynamic Architecture of a Developing Organism. Kluwer Acad. Publishers. Dordrecht/Boston/London. 238 P.
- Belousov, L.V. 2006. Ultraweak photon emission as a tool for analyzing collective processes in cells and developing embryos. In: Biophotonics and Coherent Systems in Biology (L V Belousov, L.V., Voeikov, V.L. and Martynyuk, V.S. eds). pp. 139–158. Springer. N.Y.
- Belousov, L.V. 2008a. “Our standpoint different from common...” (Scientific heritage of Alexander Gurwitsch). Russ. J. Devel. Biol. 38: 307–315.
- Belousov, L.V. 2008b. Mechanically based generative laws of morphogenesis. Physical Biology 5: 015009
- Belousov, L.V. 2011. Nomothetics and idiography in developmental biology. Theoretical Biol. Forum 104: 15–34.
- Belousov, L.V. and V.I. Grabovsky 2003. A geometro-mechanical model for pulsatile morphogenesis. Computer Methods in Biomech. and Biomed. Engineering 6: 53–63.
- Belousov, L.V., Labas, Ju.A., Kazakova, N.I. and A.G. Zaraisky 1989. Cytophysiology of growth pulsations in hydroid polyps. J. exp. Zool. 249: 258–270.
- Blumenfeld, L. A. 1983. Physics of Bioenergetic Processes. Springer, Berlin.
- Bohm, D. 1980. Wholeness and the Implicate Order. Routledge, London.
- Chialvo, D.R. 2010. Emergent complex neural dynamics. Nature Physics 6: 744–750.
- Curie, P. 1894. De symmetrie dans les phenomenes physique: symmetrie des champs electrique et magnetique. J. de Physique Ser. 3: 393–427.
- De Robertis, E.M. 2006. Spemann’s organizer and self-regulation in amphibian embryos. Nat Rev. Mol. Cell Biol. 7: 296–302.
- Del Giudice, E and 6 coauthors. 2005. Coherent Quantum Electrodynamics in Living Matter. Electromagnetic Biol. and Med. 24: 199–210.
- Driesch, H., 1891. Entwicklungsmechanische Studien. I. Der Werth der beiden ersten Furchungszellen in der Echinodermentwicklung. Experimentelle Erzeugung von Theil- und Doppelbildungen. Z. wissenschaftliche Zoologie 53: 160–184.
- Gilbert S.F., J.M. Opitz and R.A. Raff 1996. Resynthesizing evolutionary and developmental biology. Dev Biol. 173: 357–372.
- Gilbert, S.F. 2010. Developmental Biology. Sinauer Ass. Sunderland Mass USA.
- Goodwin, B. 1994. How the leopard changed its spots. Weidenfeld & Nicolson, London.
- Gurwitsch, A.G. 1912. Die Vererbung als Verwircklichungsvorgang. Biol. Zbl. 22: 458–486.
- Gurwitsch, A.G. 1914. Der Vererbungsmechanismus der Form. W. Roux’ Arch Entwmech. Org. 39: 516–577.
- Gurwitsch A.G. 1922. Ueber den Begriff des embryonalen Feldes. W. Roux’ Arch Entwmech. Org. 51: 388–415.

- Gurwitsch A.G. 1944. A Theory of Biological Field. Sovetskaya Nauka, Moskva (in Russian).
- Gurwitsch A.G. 1947. The concept of "whole" in the light of the cell field theory. In: Collection of Works on Mitogenesis and Biological Field Theory (A.G. Gurwitsch ed.) pp. 141–147. USSR Acad. Med. Sci. Printing House, Moskva (in Russian).
- Gurwitsch A.G. 1991. Principles of Analytical Biology and a Theory of Cellular Fields. Nauka, Moskva (in Russian).
- Haken, H. 1978. Synergetik. Springer-Verlag, Berlin Heidelberg New York.
- Harrison, R.G. 1918. Experiments on the development of the fore-limb of *Amblystoma*, a self-differentiating equipotential system. *J. exp. Zool.* 25: 413–461.
- Levin, M. 2012. Morphogenetic fields in embryogenesis, regeneration and cancer: Non-local control of complex patterning. *BioSystems*, 109: 243–261.
- Lewis, E.B. 1978. A gene complex controlling segmentation in *Drosophila*. *Nature* 276: 565–570.
- McClare, C.W.F. 1971. Chemical machines, Maxwell's demon and living organisms. *J. theor. Biol.* 30: 1–34.
- Mocek, R. 1974. W.Roux – H Driesch. Zur Geschichte der Entwicklungsphysiologie der Tiere ("Entwicklungsmechanik"). Fischer, Jena.
- Nicolis, G. and Prigogine, I. 1977. Self-Organization in Non-Equilibrium Systems. Wiley, N.Y.
- Opitz, J.M. and R.A. Raff 1996. Resynthesizing evolutionary and developmental biology. *Dev. Biol.* 173: 357–372.
- Poincare, H. 1893. Les methods nouvelles de la mecanique celeste., Gauthier-Villars, Paris (Dover edition, 1957).
- Popp, F.-A., K.H. Li and Q. Gu eds 1992. Recent Advances in Biophoton Research and its Applications. World Scientific, Singapore.
- Prigogine, I. 1980. From being to becoming. Freeman and Co, N.Y.
- Rapoport, I.A. 1996. Selected works. Nauka, Moskva (in Russian).
- Shih J. and Keller R. 1992. Cell motility driving mediolateral intercalation in explants of *Xenopus laevis*. *Development* 116: 901–914.
- Teufel, T. 2011. Whole that causes their parts: organic self-reproduction and the reality of biological teleology. *Stud. Hist. Philos. Biol. Biomed. Sci.* 42: 252–260.
- Thom, R. 1970. Topological models in biology In: Towards a theor. Biol., 3. Drafts (C.H. Waddington ed.) pp. 89–116 Edinburgh Univ. Press, Edinburgh.
- Waddington, C. H. 1940. Organizers and genes. Cambridge University Press, Cambridge.
- Weiss, P. 1939. Principles of development. Cambridge Univ. Press, Cambridge.
- Wolpert L. 1969. Positional information and the spatial pattern of cellular differentiation. *J. theor. Biol.* 25: 1–47.
- Wolpert L. 1996. One hundred years of positional information. *Trends in Genetics* 12: 359–364.