STUDIA METODOLOGICZNE
NR 37 • 2016, 155–173
DOI: 10.14746/sm.2016.37.9

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Analogy-Making in Biology. An Essay on the Comparative Spirit

Fate has been kind
to me thus far
(…)
My yen for comparison
might have been taken away

Wisława Szymborska *Among the multitudes*

What is the visible and what is the invisible?

Paracelsus *Paragranum*

ABSTRACT. Analogy-making fulfills many important functions in biology – heuristic, systematizing, explicative, assertive-justifying, illustrative-didactic, although the term ‘analogy’ is rarely used nowadays. In the paper we present examples of analogy-making in biological sciences and in the teaching of biology.

KEY WORDS: analogy, anomaly, biology, evolution, development, evo-devo

1. Introduction

As noted by Minelli [2009] *the comparative spirit that for a long time had seemed to be lost in many areas of biology seems to have given new life*. In recent years, comparative studies in biology have contributed to many unexpected discoveries, which have, among other things, affected the development of a new, significant interdisciplinary trend known as evolutionary developmental biology (evo-devo in short).

In the present paper we provide answers to the following questions: what functions does reasoning by analogy play in biology and what is its specificity in this branch of science?

Our paper is just an outline of the issues, as it is impossible given the limited scope of this text to present the vast range of the problems related to the application of reasoning by analogy in biology.

The structure of the paper is as follows. We discuss briefly the role of analogical reasoning in the development of biological sciences and in the teaching of biology. We present the functions of analogy-making in various fields of biology and bionics separately. We also approach the issue of the scope of application of analogical reasoning in biology.

2. Analogies discovered in nature and dynamics of biology

The development of life sciences is largely the history of the formulation of different types of reasoning referring to analogies discovered in nature. It is impossible to imagine life sciences without the systematizing function implemented by these sciences, and the systematizing function – without recognizing the structural similarities between the observed objects. A standard example of systematization in natural sciences is biological classification of living organisms.

As for the substantiation of claims in natural sciences, analogy has a number of complex cognitive functions. There are areas of natural sciences, in which the only possible way of substantiating claims is reasoning by analogy, based on the presentation of the appropriateness of certain relationships between phenomena belonging to the field under investigation and the relationships between the phenomena in another, better known field [Biela, 1989]. For instance, drawing conclusions about the biology of animals in ancient geological epochs on the basis of the knowledge of modern animals (which does not always have to be true) or making inferences about the course of a developmental process in a given group of animals on the basis of the development of a single species known in this respect (the species *Strigamia maritima* can serve as an example here as this is the only species thus far known in terms of its embryonic development among centipedes from the order Geophilomorpha [Brena, 2014]).

For many reasons, the investigation of the biology of the majority of species is impossible. Therefore only certain, selected species are used in studies – the so-called model organisms. These are species whose breeding and observation are possible and convenient. These organisms, for instance, have short development cycles, and they easily reproduce and develop in breeding conditions. The most famous model species of animals include the fruit fly *Drosophila melanogaster*, the worm *Caenorhabditis elegans* or the mouse *Mus musculus*, model species in the case of plants include, for instance, the thale cress *Arabidopsis thaliana* or the Asian rice *Oryza sativa*, a model amoeba is *Dictyostelium discoideum* [Twyman, 2003; Minelli, 2009]. The observation of life processes of these species, and also – especially in recent years – genetic and molecular studies, provide information that is used by analogy to explain various aspects of the biology of other species, which for different reasons are not available for direct investigations. Obviously, this type of inference should be made with great caution. Many times it has been shown that closely related organisms feature substantial differences, for instance, in terms of their development [Twyman, 2003; Krakauer et al., 2011].

The data on some processes or phenomena obtained experimentally in animals is very frequently used for drawing conclusions about their application in humans. Therefore it is through analogy that conclusions are drawn about the action of drugs, various chemicals, mutagens, teratogenic agents etc. For example, by observing the reactions of organisms and the behavior of animals in space the impact of similar conditions on the human body can be predicted. First – innovative operations before they are carried out in humans are carried out in animals.

Forensic medicine makes use of observations of animal corpses as the basis of knowledge about the processes of decomposition of human corpses, which is extremely helpful in determining the time and circumstances of death [Bajerlein et al., 2011].

Entire fields of biology – such as comparative anatomy and morphology, taxonomy, molecular genetics – make reference to analogical reasoning. Evolutionary and phylogenetic studies also rely on the comparison of the characteristics of different organisms – in search of similarities which provide evidence for affinities between organisms.

Jacob [1993] also emphasizes that: "in order to know an object, none of the analogies by which it is linked to things and other beings should be neglected."

The entire field of science – bionics (biomimetics) – is based on the use of analogy. This interdisciplinary field of science investigates the structure and the principles of the functioning of organisms so that the same or very similar solutions can be applied in technology and architecture – in the design of airplanes, ships, buildings (Figs 1 & 2) etc. Steadman [2008] recalls the concept of *organic analogy* – which means an organism as a model for design.

Fig. 1. The Sagrada Familia – Gaudi's temple in Barcelona. An example of organic architecture, photo by Ewa Malinowska

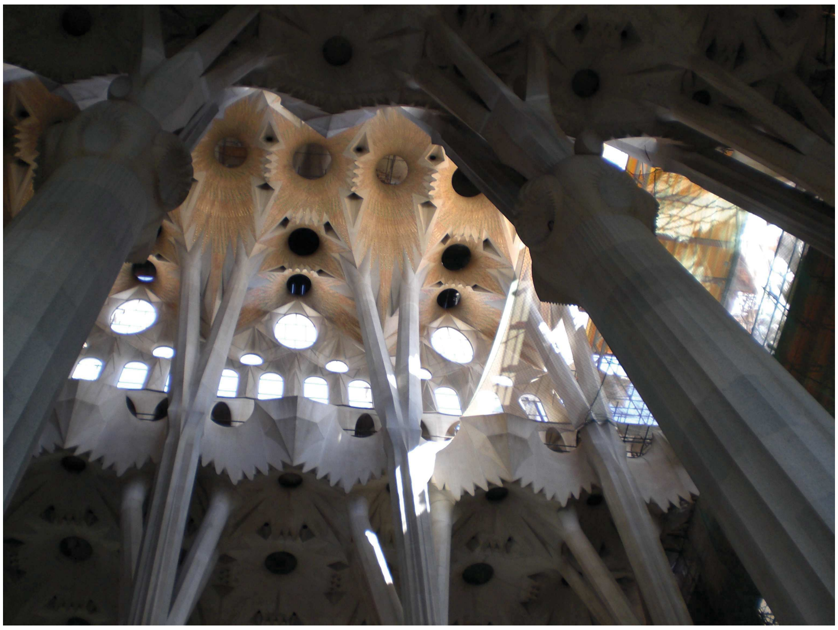


Fig. 2. The Sagrada Familia, Gaudi's temple in Barcelona (interior), photo by Ewa Malinowska

The most accurate imitations of the structure of body organs are used in prosthetics [Kuhlmann, 2011; Rattay, 2011]. "Biomimetics makes use of functional analogies, processes, mechanisms, strategies of information derived from living organisms" [Gruber, 2011]. Some important technology problems in engineering application have been resolved by drawing the inspiration of biological systems [Ren and Li, 2013].

The emergence of a new trend in research – evolutionary developmental biology – was largely due to bold comparisons made despite skeptics convinced of their futility. It was not believed that, for instance, genetic studies of the fruit fly could in any way be useful in the studies of vertebrates, including humans. However, it turned out that there was a big surprise awaiting the skeptics [Carroll, 2005]. Let us quote here a fragment of a great book by Carroll [2005, p. 71]: "The discovery that the same set of genes control the formation and pattern of body regions and body parts with similar functions (but very different designs) in insects, vertebrates, and other animals has forced a complete rethinking of animal history, the origins of structures and the nature of diversity. Comparative and evolutionary biologists had long assumed that different groups of animals, separated by vast amounts of evolutionary time, were constructed and had evolved by entirely different means. The connection between members of some groups – among the vertebrates, for example, or between vertebrates and other animals with a notochord – was well established. But between flies and humans, or flatworms and sea squirts… no way!"

3. The role of analogy in the teaching of biology

Illustrative analogy or metaphors are used in the teaching process to make students familiar with new, unknown content by means of images or similar aspects of the knowledge they already have. Although it is difficult to imagine teaching biology without providing accurate analogies/metaphors, there are studies that undermine the value of the application of analogy in the teaching process [review of the cases in a study by Venville & Treagust, 1997].

One of the most famous analogies was applied by Darwin [2001] when comparing the process of evolution to a large, branching tree. However, in explaining the mechanism of evolution of the living world – natural selection – he used the analogy of artificial selection made by man in order to get new breeds of domesticated animals and plants. (This comparison is considered a weakness in Darwin's theory [Venville & Treagust, 1997]).

An analogy is often used to explain the evolutionary events in Earth's history, by comparing the history of our planet (approximately 4.6 billion years) to a 24-hour day. This helps make students aware of the time scale and place the events in time, which would otherwise be very difficult to understand. Every second in this model corresponds to tens of thousands of years in real time. One can see that in this perspective, for example, the first cell formed at around 5:30 A.M., and the last animal ancestor in the line leading to humans emerged at 11:58 P.M. [e.g. Campbell et al., 2012].

Another commonly applied accurate analogy for the description of the respiration process is its comparison with the combustion process (this analogy is derived from A. Lavoisier, the discoverer of the role of oxygen in the combustion process).

Venville & Treagust [1997] showed using many examples that analogies may be able to improve student understanding of some biological concepts, however, they have some constraints, which teachers should be aware of.

4. The role of analogy in classification structures

The word "classification" has two different meanings – it usually means the result of the work of a taxonomist, but it can also refer to the very act of classifying.[1]

Humans classified objects and phenomena by means of generic or collective terms until the time they possessed the ability to communicate using speech. These were probably simple classifications of great importance for the daily life and functioning – such as the division of animals and plants into edible or inedible ones, useful, harmful, dangerous ones etc. [Mayr, 1974].

Classifications in the biological sciences have been known since ancient times. Plato's famous definition of man – "Man is a two-footed, featherless animal" [Laërtius, 1853] – was derived from a classification based (as in the case of any classification) on analogical reasoning.[2] Aristotle is called the *father of biological classification*. [Mayr 1974, p. 72].

Linnaeus (1707–1778) (called the *father of taxonomy*) developed a system of the classification of living organisms, which he described in his famous work *Systema naturae* (first edition in 1735), and its principles are

[1] For the record, it should be noted in passing that the distinction between a given research activity and the result of this activity was at the basis of the systematic distinction between *pragmatic methodology* and *apragmatic methodology* made by Ajdukiewicz.

[2] See [Laërtius 1853: p. 231].

used until today. In this work, he introduced, among others, the principle of binominal nomenclature in biology.

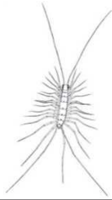
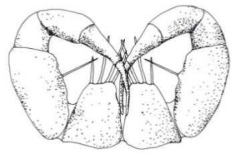
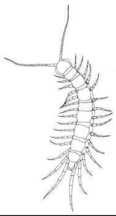
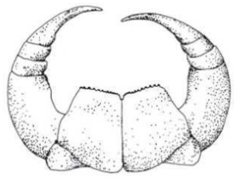
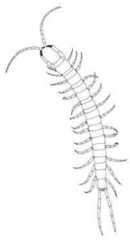
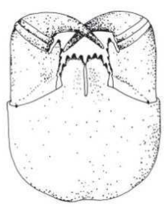
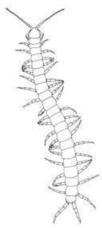
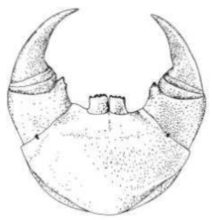
G. Cuvier (1769–1832), known as the *father of comparative anatomy*, in his work *The Animal Kingdom* (French *Le règne animal*, 1817) introduced the classification of the animal world into 4 groups – or as he called them "*embranchements*" – Vertebrata, Mollusca, Articulata and Radiata. The classification was based on four different basic body plans of animals. It was an innovative approach – Linnaeus did not use higher categories than classes [Urbanek, 2007].

An important contribution to the theory of taxonomy was made by K. Darwin (1809–1882), mainly by creating the theoretical foundations of the natural system.

At the turn of the nineteenth and twentieth centuries, the so-called population systematics (new systematics) was developed, which in its classifications, apart from the morphological structure, started taking into account all available data on the biology of organisms.

All the available biological knowledge (molecular data in particular) is also used in the development of contemporary classifications.

An example of a classification is the division of the class of centipedes (Chilopoda) into orders and families (Fig. 3). Centipedes include predatory invertebrate animals, with a segmented body, where each segment of the trunk has one pair of legs. What distinguishes all centipedes from other types of arthropods (Arthropoda) is (among others) the presence of maxillipedes fitted with poison claws containing a venomous gland (Fig. 3). Maxillipedes are considered to be the transformed first pair of legs and they are mainly used to capture their victims and introduce venom into their bodies. All centipedes feature a high number of pairs of legs – from 15 to 191 pairs and this is always an odd number. (In addition to these features, all centipedes have other features in common. However, this will not be discussed here as these features are relevant only for specialists). The living centipedes are classified into five orders: Scutigeromorpha, Lithobiomorpha, Craterostigmomorpha, Scolopendromorpha and Geophilomorpha (Fig. 3). It is obvious that within individual orders animals have certain features in common, and the differences we observe between them allow us to (and lead us to) distinguish lower taxonomic units, such as families, genera and species.

Order/Family	Habitus	Maxillipedes (examples)
Order: Scutigeromorpha Family: Pselliodidae Scutigeridae Scutigerinidae		
Order: Lithobiomorpha Family: Henicopidae Lithobiidae		
Order: Craterostigmo- morpha Family: Craterostigmi- dae		
Order: Scolopendromor- pha Family: Cryptopidae Plutoniumidae Scolopendridae Scolopendrinae Scolopocrypto- pidae		
Order: Geophilomorpha Family: Aphilodontidae Ballophilidae Dignathodontidae Eriphantidae		

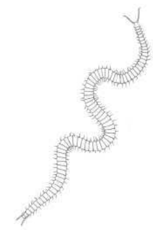
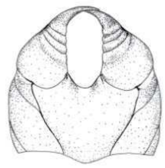
Geophilidae Gonibregmatidae Himantariidae Linotaeniidae Macronicophilidae Mecistocephalidae Neogeophilidae Oryidae Schendylidae		

Fig. 3. Division of the class of centipedes (Chilopoda) into orders and families [according to Bonato at al. 2011], characteristic habitus and an important feature common to the entire class – maxillipedes (the figures were used in the study by Leśniewska 2014)

A special category of specimens within a group of known species is formed by anomalous specimens, i.e. specimens with the morphology featuring deviations from the "normal" structure, which is manifested by the majority of individuals belonging to a given species. (Obviously, distinguishing an anomaly is always based on the knowledge of the norm, which is not always evident). A classification of morphological anomalies based on binominal nomenclature and the Linnaean hierarchical system was introduced by Isidore Saint-Hilaire [1836]. This was an important moment not only in the development of teratology, but also for comparative morphology and developmental biology. This researcher proved that among morphological anomalies found in various animals (particularly in humans) one can see similarities that allow for the distinction of certain categories. As noted by Alberch [1989], the formation of "monsters" is governed by some internal logic and it is common both to anomalous and normal forms. In the context of the application of analogical reasoning, classifications of anomalies deserve special attention. The fact of the existence of similarities among anomalous features in different specimens leads to a deeper understanding of biological processes – in particular developmental processes, especially in the case of species where the study of their development is not yet possible [e.g. Leśniewska et al., 2009]. Figure 4 presents only one type of a trunk anomaly (so-called dorsal mispairing) in a centipede species from the order Geophilomorpha – *Haplophilus subterraneus*.

This example shows that in different specimens the same type of a defect forms during ontogeny. Thus it can be assumed that the mechanism of the defect formation is similar. And this brings us to the possibility of formulating a hypothesis about the likely course of the normal and impaired development in centipedes [Leśniewska et al., 2009].

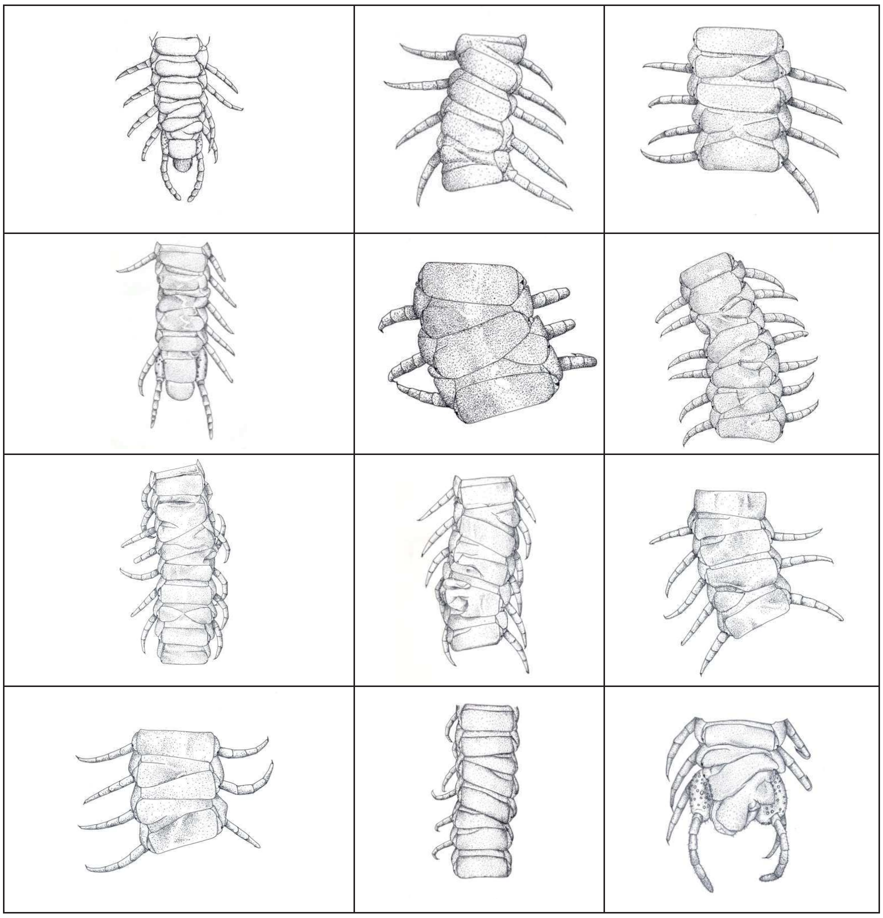


Fig. 4. Diversity of one type of an anomaly, "dorsal mispairing", in specimens of one centipede species – *Haplophilus subterraneus* (some figures were used in the studies by Leśniewska et al. 2009; Leśniewska 2012, 2014)

In the discussion of similarities between anomalies, it is worth emphasizing in passing that it was Quine who said that *the tension between law and anomaly is vital to the progress of science*.[3]

The study of the diversity of organisms combined with their comparison, description and classification has led to an important discovery that not all forms of organisms can be found in nature, and that many of them manifest limited variability. The regular development such as the occurrence of an odd number of leg-bearing segments has already been mentioned. This is a good example of limited variability [Minelli, 2009]. A similar phenomenon can also be observed in the case of anomalies – not all kinds of anomalies that we could imagine exist in nature, and some are found very rarely [Geoffroy, 1863; Alberch, 1989]. An anomaly that develops extremely rarely in centipedes is the occurrence of an even number of leg-bearing segments in a specimen [Leśniewska et al., 2009; Leśniewska, 2012]. This very interesting issue of the causes that underlie the absence of certain forms in nature has been approached by many contemporary biologists, particularly evo-devo researchers [Hall, 1999; McGhee, 2007; Minelli, 2009]. Readers interested in this topic should refer to the literature on the subject. This is only to signal that analogical reasoning is always used at various levels and stages of biological research often leading to some unexpected, new discoveries.

5. The problem of the scope of application of comparisons

Now, let us return to Curvier and the classification of animals he introduced. This scholar believed that animals belonging to different *embranchements* cannot be compared to one another. This issue was the cause of an argument he had with another great comparative anatomist – É. Geoffroy St. Hilaire, who was convinced that all animals are built according to the same plan, and therefore there are no obstacles to carry out comparisons between any species, even of the boldest kind [e.g. Hall,

3 See [Quine 1987, p. 8].

1999; Minelli, 2009]. He referred to the adequacy existing between parts of the body of different animals as analogy, and he called the system of views related to this issue as the theory of analogy (*Théorie des analogues*) [Urbanek, 2007]. (The term analogy in the sense used by Geoffroy now corresponds to the term homology, see below.)

An important contribution that É. Geoffroy St. Hilaire made was to show that it is possible to compare the structure of animals belonging to separate groups, with the assumption of profound transformations of the structure and functions, while maintaining mutual relations between respective parts [Urbanek, 2007, p. 19]. A comparison of the general plan of the structure of arthropods and vertebrates carried out by É. Geoffroy St. Hilaire (so-called Geoffroy's inversion) has become famous. This scholar tried to show that by simple inversion of an arthropod's body "upside down", the main organs of an arthropod's body are positioned in the same way as in vertebrates. Although the concept by É. Geoffroy St. Hilaire was not commonly approved by his contemporaries, the comparison made by Geoffroy has currently been recalled by evolutionary developmental biology (evo-devo) as it was discovered that morphogenetic signals determining the formation of the ventral or dorsal side in embryos are almost identical in arthropods and vertebrates [De Robertis & Sasai, 1996; Urbanek, 2007; Minelli, 2009]. Thus modern research in molecular biology and evo-devo largely confirmed the approach presented by Étienne Geoffroy Saint-Hilaire. It turned out that animals with most distant affinities have a lot in common. Comparative studies have led to the discovery of the unity of the structure and function of various organisms at different levels and in different aspects – in relation to the cells, tissues, physiology, and development. Recent studies have shown that different organisms are composed largely of the same set of genes. The diversity of forms is due to changes in the regulatory systems governing the expression of these genes [Hall, 1999; Carroll, 2005]. The creative potential of these regulatory systems is due to their combinatorial structure. As stated by Jacob [1997] – all living creatures seem to be formed from the same modules, arranged in different ways. The living world is as if it were a combination of a set of a finite number of elements, which resembles a gigantic puzzle – a result of constant shuffling of genes by evolution.

6. Analogy and homology as fundamental concepts of comparative biology

In biology, the use of analogical reasoning differs from the way in which the concept of "analogy" is applied. The concept of analogy in biology refers to similarities arising from the adaptation of different organisms to similar habitats, and thus similarities related to the function. A concept that is used to define similarities showing the affinity of organisms is the concept of homology.

We owe the clarification of the concepts of analogy and homology in zoology to Richard Owen [1843]. According to this author:

(1) "Analogue" – "A part or organ in one animal which has the same function as another part or organ in a different animal";

(2) "Homologue" – "The same organ in different animals under every variety of form and function."

A classic example of analogous organs are the wings – of an insect and the wing of a bird or a bat (their similarity is related to a similar function). A classic example of homologous organs is the human arm and the wing of a bird (although they look different, their structure is similar, which is due to their affinity).

The introduction of this distinction, and thus making us aware of the existence of two types of similarities, has greatly contributed to the development of comparative biology [Urbanek, 2007, p. 36].

Although the concept of analogy therefore relates only to functional similarities, it has greatly contributed to the development of biology, which Konrad Lorenz talked so beautifully about during a lecture after receiving the Nobel Prize [Lorenz, 1974]. In particular, he pointed out to the role of analogy between the behavior of humans and birds in the theory of animal behavior developed by him.

The basic concept of comparative biology is thus the concept of homology. Owen believed that homology relations can be of three types and he therefore distinguished between *special homology*, *general homology* and *serial homology* [Urbanek, 2007].

A problem associated with the identification of homology features is the issue of homology criteria. According to Owen, the basic criterion was the mutual position of parts, their mutual relationship within a larger structure. This was also in line with the views expressed by É. Geoffroy Saint-Hilaire and his "principe des connextions". Owen attributed a lesser role to embryonic development, while a greater role was attributed by him to the existence of a series of gradual transfers in the structure of organs, from the simplest to the most complex form [Urbanek, 2007].

One would expect that features of similar genetic and developmental background would be homologues, and features that are phylogenetically homologous would show similar genetic and developmental adjustment. In practice, however, this expectation proved to be false, which led to the introduction of the concept of *biological homology* [Wagner, 1996].

In recent years, the development of evo-devo enabled the introduction of new criteria for homology. Currently, homology should not be viewed in an all-or-nothing relationship, but in a combinatorial way [Minelli, 1998, 2009, 2016; Minelli & Fusco, 2013].

It seems that long disputes about the understanding and the criteria for homology have not led to a common view on this issue.

In recent years, one rarely comes across the concept of analogy in literature, while homologies are often described as synapomorphic features [Nelson, 1994].

7. Conclusions

According to Biela [1989], analogy can fulfill the following functions for scientific knowledge:

- heuristic (posing problems and putting forward scientific hypotheses),
- systematizing (distinguishing and organizing elements, conceptual categorization, typologization),
- explicative,
- assertive-justifying,
- illustrative-didactic.

Analogy-making fulfills all these functions in biological sciences, although the term *analogy* is rather rarely used. Significant similarities between organisms, showing their affinity, are referred to as *homology*, and in recent years this concept has been undergoing a transformation.

Inference by analogy is made in natural sciences in order to find answers to questions about the affinity of organisms, the course of evolution, phylogeny, developmental mechanisms, and thus it fulfills the argumentative and heuristic functions. It also has a practical dimension – it is used in bionics, pharmacology and medicine. It fulfills illustrative, educational and systematizing functions. It is a source of creative ideas leading to the development of this field of science.

Finally let us focus on the linguistic aspects. Currently main meanings of the Greek word 'αναλογία' (a feminine noun) are *relation*, *proportion*, and *ratio*. But there is a masculine noun 'αναλογισμός' and it means *fresh calculation*, and *reconsideration*. The word appears for example in the third book of *The History of the Peloponnesian War* (Chapter 36). It seems that the range of applications and the results of the use of analogy-making within the dynamics of biology rather quite aptly reflect the meaning of this Greek word.

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