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Applying graph extension function in biology

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ABSTRACT

Arbitrary systems, will it be biological, physical, cybernetical, etc. may be described by a mathematical function, namely by a graph extension function, which we also call hierarchical function (and which mathematically shows hierarchical nature of science). This function can be also used to describe mathematical objects themselves, which in the paper is shown on the example of the action of the graph extension function on the set of integers.

A new theory of graph extensions, similar to group extension theory, is outlined. A theorem about the equivalence of different extension functions is proved. There exists an isomorphism between the modified functional graph of the cell (functional block-scheme) and the morphological graph of the cell (the graph expressing topological membrane intertransformations of the cell) which expresses the most essential features of for the biology of the cell and captures one of the specific differences between living and non-living systems.

It is shown that the construction of the graph of a complex organism from the primordial graph given by Rashevsky is nothing but an extension of the primordial graph by the graph extension function.

It is described that there exist morphisms from biological graphs described by various authors to our functional graph.

INTRODUCTION

A possibly single mathematical function describing the universe is mentioned in an article[1] by the Nobel Prize winner Swedish physicist Hannes Alfvén where he asks whether in the academia scientific circles there exists a belief that the nature of the universe can be described by a single mathematical formula. The renowned physicist Michio Kaku in his online lectures[2] talks about the similar things. In the present work, applications of the graph extension function acquire universal character and it is not excluded that this might be the function sought for by Alfvén, Kaku and the Pythagorean school. In the past, the science was unified and only later disbanded into separate sciences, whereas the graph extension function potentially unites different sciences into one whole science. Unfortunately or fortunately, it shows that during the last 2000 years nothing new is created in the science and what is created are the new forms of the old. The same situation is in the art, etc. One of the aims of this function is also the unification of the mathematics itself.

In the paper[3] we have described the notion of trivial graph extension. In the paper[4] we have described the notion of nontrivial graph extension and gave several examples of its applications in describing some relatively subtle phenomena in behavior of complicated systems.

In that paper, we expressed guess that probably the construction of a graph of a complex biological organism starting from a much simpler (“primordial”) graph as considered by Rashevsky[5,6] can be also described using our formalism of graph extensions. Presently we have obtained such description and in this presentation we will outline very briefly the corresponding construc-

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tion.

We have also established that the formalism of graph extensions can be used to model essential aspects of distinguishing structures characteristic for life from other kinds of structures. More concretely this distinction manifests itself in the isomorphism between morphological and functional graphs of a cell. This isomorphism has been seemingly observed by us for the first time in[4]. After that, an issue is raised to extract from the notion of graph extension a single mathematical function which will encode the aforementioned aspects. Such function might serve as a key to distinguishing life forms from other kinds of matter in particular.

This function contains features common for various fields of science, by which reason it can be called unifying graph extension function. At the same time this function can be called hierarchical since, as we have shown in[2], a graph reflecting some type of phenomena is transformed under a graph extension into a graph corresponding to phenomena of lower (deeper) level.

Let us note that similar approach to modeling various hierarchical systems, but using categories rather than graphs, has been developed in[7].

The graph extension function can be also used in mathematical research to describe various kinds of mathematical processes which in fact may be considered as its particular cases.

In fact moreover the mathematical function derived from graph extensions has a potential to detect similarities and differences between various scientific approaches. In particular it gives precise formal meaning to the ideas of N. Rashevsky presented in[8], about common consideration of patterns characteristic for development of such diverse research fields as physics, biology and sociology. More concretely we claim that it is possible that each of these research fields can be assigned a particular kind of such graph extension function which will reflect their essential structural characteristics.

As for what concerns biology, this function not only unifies its different fields, but also will help us in finding a so to say "periodic system of cell types" (the term by Savostyanov[9] which may become indispensable in solving problems in e.g. oncology. Moreover calculating various extensions may help us to find entirely new organisms, etc.

RESULTS AND DISCUSSIONS

Let us start by recalling that by a *graph* we mean a collection G of the following data: the set V_G of *vertices* of G and the set I_G of *arrows* of G, where each arrow i is assigned a pair (v,v') of distinct vertices called *source* and *target* of G. It is required that there is not more than one arrow with given fixed source and target. Simplest examples of graphs are given by *discrete* graphs – those without any arrows, and by the opposite extreme, namely the *indiscrete* graphs – those in which each pair of vertices is connected by an arrow in both directions.

In few words, the notion of graph extension introduced in[4] can be described as follows. An extension of a graph G by a family $(G_v)_v$ of other graphs indexed by vertices of G is a graph H together with a surjective map $\sigma{:}H\to G$ such that

$$\sigma^{-1}(v) = G_v$$

for each vertex v.

The central idea of the paper[4] is the notion of the *extension function* associated to such an extension. This is a certain partial map

$$f:\left(\coprod_{v\in V_G} V_{G_v}\right)\times I_G \to \coprod_{v\in V_G} 2^{V_{G_v}}$$

satisfying specific conditions described in[4]. It turns out that any graph extension is completely described by the corresponding extension and that in the significant variety of situations graph extension functions are very useful in describing peculiarities of behavior of complex systems. Corresponding examples were given in[4]. Here we briefly describe another example which is concerned with more refined description of phenomena introduced in[10,11]. Before that however let us mention two simpler examples of graph extensions.

First, it is very easy to describe all possible extensions of a discrete graph. Any extension of a discrete graph with the set of vertices V is determined by an arbitrary family of graphs $(G_v)_{v\in V}$. Indeed the corresponding extension function must be

$$f:\left(\coprod_{v\in V_G} V_{G_v}\right)\times I_G \to \coprod_{v\in V_G} 2^{V_{G_v}}.$$

So the domain of f must be the empty set, and there is always a unique function of this kind.

To prove this: (1)

Suppose the graph H is an extension of a graph G by the family $(G_v)_{v \in V_G}$.

Let us establish an isomorphism between preimages of all vertices of the graph G and the corresponding graphs G_v from the family $(G_v)_{v \in V_G}$. To each vertex $v \in V_H$ of the graph H let us assign the n-tuple (v^α, v), where the second coordinate is the image of the vertices v^α of the graphs from the family under the epimorphism $\sigma: H \to G$ of the graph H onto the graph G while the first coordinate v^α is the image of a vertex of G_v under the isomorphism between it and $\sigma^{-1}(v)$.

Suppose $v \in V_G$ is a source of some arrow $i \in I_G$ and $v' \in V_G$ is the target of the arrow i. Let (v^α, v) be the source of any arrows in I_H and the second coordinates of targets of these arrows are the vertices $\{(v^{\alpha_1}, v'), (v^{\alpha_2}, v'), \ldots, (v^{\alpha_m}, v')\} \subseteq V_{H'}$, where $V_{G_v} = \{v^{\alpha_1}, v^{\alpha_2}, \ldots, v^{\alpha_m}\}$. Take the pair (v^α, i) and assign to it the set

$(v^\alpha, i) \mapsto \{v^{\alpha_1}, \ldots, v^{\alpha_m}\}$.

Similarly assigning to all pairs (v,i) subsets of V_{G_v} we obtain the extension map

$$f:\left(\coprod_{v \in V_G} V_{G_v}\right) \times I_G \to \coprod_{v \in V_G} 2^{V_{G_v}} \qquad \textbf{(2)}$$

In case when a graph G and a family $(G_v)_{v \in V_G}$ of graphs are given together with the map

$$f:\left(\coprod_{v \in V_G} V_{G_v}\right) \times I_G \to \coprod_{v \in V_G} 2^{V_{G_v}}$$

then one can construct an extension H of the graph G by the family $(G_v)_{v \in V_G}$ and the map f.

Indeed, the set of vertices V_H of the extension H will be $V_{G_v} \times V_G$. As a part of the set I_H will be taken the set $I_{G_v} \times V_G$, and the remaining part of I_H will be constructed as follows:

Take any $(v^\alpha, v) \in V_{G_v} \times V_G$. Suppose $v \in V_G$ is a source of some arrows in I_G and $i \in I_G$ is one of those arrows. Suppose v' is the target of i. Now let us construct new arrows in H whose source will be (v^α, v) and targets will be the vertices

$(v^{\alpha_1}, v'), (v^{\alpha_2}, v'), \ldots, (v^{\alpha_m}, v') \in V_{G_v} \times V_G$,

where

$f(v^\alpha, v) = \{v_1, v_2, \ldots, v_m\} \in 2^{V_{G_{v'}}}$,

where

$m \le$ card V_{G_v}. **(3)**

Let us now prove a criterion of equivalence of two extension maps.

Suppose given two isomorphic extensions H_f and H_g of a graph G by the family $(G_v)_{v \in V_G}$ and the two extension maps

$$f:\left(\coprod_{v \in V_G} V_{G_v}\right) \times I_G \to \coprod_{v \in V_G} 2^{V_{G_v}}$$

and

$$g:\left(\coprod_{v \in V_G} V_{G_v}\right) \times I_G \to \coprod_{v \in V_G} 2^{V_{G_v}}$$

Under the isomorphism $H_f \cong H_g$ to each vertex $(v^\alpha, v) \in V_{H_f}$ is assigned a vertex $(T(v^\alpha, v)) \in V_{H_g}$. Here V_{H_f} and V_{H_g} be the vertex sets of the extensions H_f and H_g respectively, while T is a map

$T: V_{G_{v^\alpha}} \times V \to V_{G_{v^\alpha}}$

defined by $T(v^\alpha, v) = v^{\alpha'}$ and to each arrow $(i^\alpha, v) \in I_{H_f}$ corresponds and arrow $\pi((i^\alpha, v), v) \in I_{H_g}$, where I_{H_f} and I_{H_g} are the arrow sets of H_f and H_g respectively and π is a map $\pi: I_{G_v} \times V \to I_{G_v}$ defined by $\pi(i^\alpha, v) = i^{\alpha'}$.

The maps T and π induce automorphisms $T_{v^\alpha}: G_v \to G_v$ defined by

$v^\alpha \mapsto T(v^\alpha, v)$,

$i^\alpha \mapsto T(i^\alpha, v)$.

Let us now take an arrow $i \in I$ with the source v and target v' in the graph G. Let us take in H_f some vertex $(v^\alpha, v) \in V_{H_f}$. The vertex (v^α, v) is the source of some arrows from whose target is . Let be the set of those arrow targets

$W_1 = \{(v^1, v'), (v^2, v'), \ldots, (v^m, v')\} \in V_{H_f}$,

$f(v^\alpha, v) = \{v^1, v^2, \ldots, v^m\} \in 2^{V_{G_{v^\alpha}}}$.

Let $(T(v^\alpha, v), v^\alpha) \in V_{H_g}$ in H_g.

Suppose this vertex is a target of some arrows in H_g with target v'. Let W_2 be the set of arrows

$W_2 = \{(v^{\alpha_1^*}, v'), (v^{\alpha_2^*}, v'), \ldots, (v^{\alpha_m^*}, v')\}$

where

$g[T(v^\alpha, v), i] = \{(v^{\alpha_1}, v'), (v^{\alpha_2}, v'), \ldots, (v^{\alpha_m}, v')\} \in 2^{V_{G_v}}$.

This by $H_f \approx H_g$ gives

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$T(W_1) = g[T(v^\alpha, v), i]$

Definition

Suppose given a graph G, a family of graphs $(G_v)_{v \in V_G}$ and extension maps f and g. We will call the extension maps f and g equivalent, if there exist such maps $T: V_\alpha \times V \to V_\alpha$, for each arrow $i \in I$ with source v and target v', which satisfies (1).

Theorem

Suppose given a graph G, a family of graphs $(G_v)_{v \in V_G}$ and extension maps f and g. If f and g are equivalent in the sense of the above definition, then the extensions H_f and H_g of the graph G by the extension maps f and g are isomorphic.

Proof

Consider the extensions H_f and H_g of the graph G by $(G_v)_{v \in V_G}$ and the maps f and g respectively. Take any vertex $(v^\alpha, v) \in V_{H_f}$. Let an arrow i in G have source v and target v'. Suppose that (v^α, v) is the source of some arrows in H_f whose second component is v'. Let W_1 be the set of targets of these arrows,

$W_1 = \{(v^1, v'), (v^2, v'), \dots, (v^m, v')\} \in V_{H_f}$,

where

$f(v, i) = \{v'^1, v'^2, \dots, v'^m\} \in 2^{V_{G_{v'}}}$.

Since f and g are equivalent, there exists a map $T: V_\alpha \times V \to V_\alpha$ such that there is a vertex $(T(v^\alpha, v), v)$ of H_g and a set of vertices

$W_2 = \{(v^{*1}, v'), (v^{*2}, v'), \dots, (v^{*n}, v')\}$

with

$g[T(v^\alpha, v), i] = \{(v^{*1}, v^{*2}, \dots, v^{*n})\} \in 2^{V_{G_{v'}}}$.

But then the equality (1) holds and this implies $H_f \approx H_g$.

For a slightly more elaborate example, let *Z* be the following graph: its vertices are all integer numbers, and there is one arrow from any integer *n* to the integer *m* if and only if $n < m$. This is by the way an example of a *transitive* graph. Next let the following family of graphs be given: for each *n*, the graph G_n has the set of vertices equal to the set of all real numbers in the interval $[n,n+1)$, i. e. all real numbers *r* satisfying $n \le r < n+1$. This family fits into a graph extension which produces the set of all real numbers *R*, with the function σ assigning to a real number its integer part. It is easy to see that the corresponding extension function is given as follows: $f(r,i)$ is defined if and only if the arrow *i* starts at the integer part of *r*, and in that case one has

$f(r,i) = [m,m+1)$,

where *m* is the integer at which the arrow *i* ends.

In future publication we are planning to address relationship between graph extensions and category theory and relationship between graph extensions and dimensions in physics.

We shall now show that there is isomorphism between functional graph D' (Figure 1) and the morphological graph A (Figure 2). Compared to the graph called D in[4], this graph D' is modified. It will be natural if we construct a morphism between *these graphs* in the following way: we shall attribute function "assimilation" function of the functional graph D' (Figure 1) to the plazma membrane(PL) component of the morphological graph A. We shall attribute the function of "decomposition" to the "lyzosome"(Ly), the "storage" to the Golgi complex(GC), the "synthesis" to the endoplasmic reticulum(ER), the "excretion" to the residual

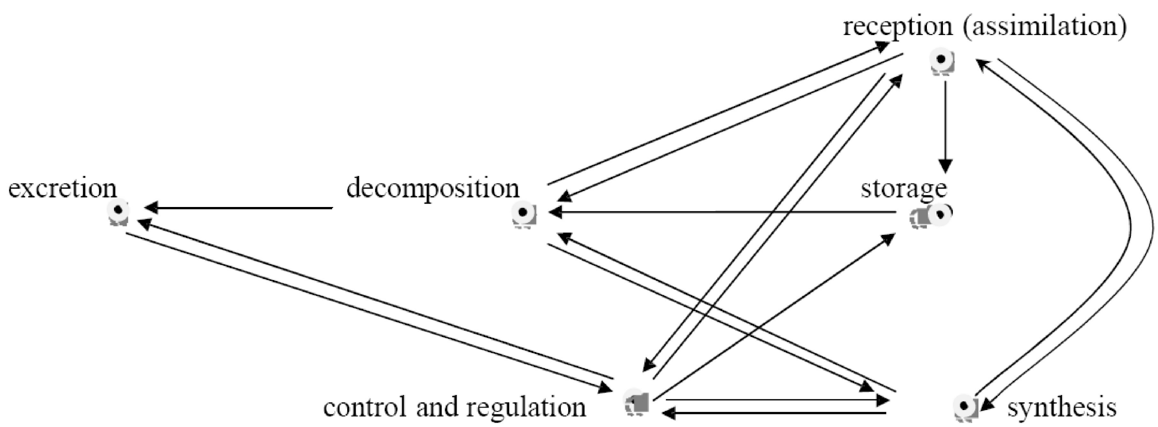

Figure 1 : The functional graph D'

body(RB), the "control and regulation" to the nuclear membrane(Nm).

The morphism constructed between the graphs *A* and *D'* in such a way is isomorphism. In other words, we correlate the functions performed by these membranes in the cell with the different types of membranes. Thus, the directions of morphological and functional relations coincide with each other.

Isomorphism between the functional graph (the functional block-scheme) and the morphological graph (the morphological block-scheme) is an important fact, it accounts for the essence of circulation in the cell. Reconstructions of membranes, when their connectedness and the genus of the surface change, constitute the necessary conditions for the "administrative" control of the cell. It is most probable that the cell differs from nonbiological systems in this point, that the components performing the vital functions transform into one other.

In our earlier work we raised the question whether the circulation of membranes as the morphological graph is the structural expression of the the functional graph, i.e. the graph of vital functions, and one of the most specific signs for the biology of the cell, and indeed life in general. Now we can give a positive answer to this question. The six mutually related functions performed by those membranes which are reconstructed in ontogenesis are the cause, i.e. the mechanism, of the reconstruction.

Let us now turn to the example corresponding to Rashevsky's work[5,6]. Rashevsky describes generation of more complex graphs from simple primordial ones. For simplicity let us assume that the primordial graph consists of only two vertices v_0 and v_1 and one arrow *i* from the first to the second. That is, *G* has the form

$$v_0 \xrightarrow{i} v_1$$

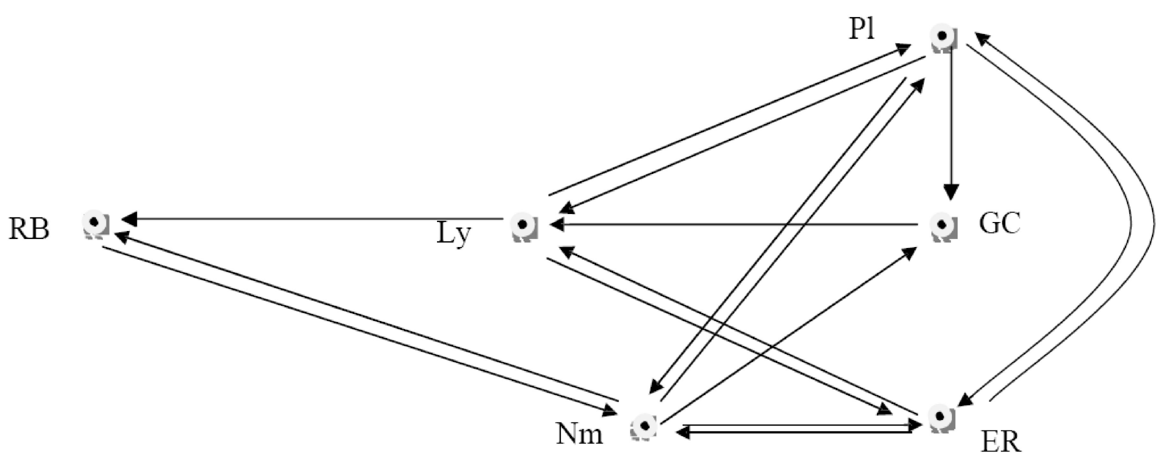

Figure 2 : Morphological graph (A) (the morphological block scheme of the cell) -the graph expressing membrane intertransformations of the cell

For this case he assigns to each vertex a new graph; thus we have in addition two graphs G_0 and G_1. In his case these are in fact the same new graph, the so called functional graph *D'*.

Between two copies of *D'*, Rashevsky assigns additional arrows corresponding to the single arrow from v_0 to v_1, namely each arrow of *D'* gives an arrow between corresponding vertices, but from the vertex in the first copy to the vertex in the second.

This structure can be construed as a graph extension in a straightforward way. The corresponding extension function has the following form:

$f(v'_0,i)$ = **{the set of those vertices of the second copy of *D'*, to which there is an arrow in *D'* from v'_0}**

for any vertex v'_0 of the first copy of *D'* and

$f(v'_1,i) = \varnothing$

for any vertex v'_1 of the second copy of *D'*.

It must be noted that, although it is intuitively clear that we have a graph extension here, Rashevsky never mentions any notion of this kind in his work.

It must be mentioned that G. Savostyanov, renowned specialist working at the Oncology Institute in St. Petersburg, in[9] argued that developing an analog of the periodic system for graphs expressing properties of cells and organisms would be necessary in the research of tumor development. However our approach is radically different in that he never used any mathematical methods. Exactly the mathematical notion of

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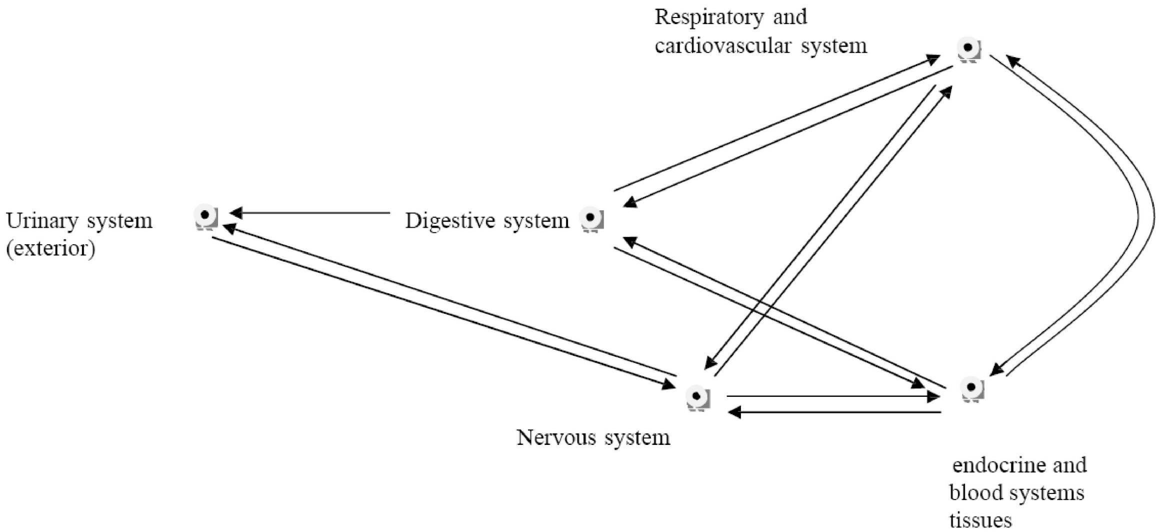

Figure 3 : The Chauvet graph of an organism

graph extension lying at the very base of our method is perfectly suitable for developing such a concept of a periodic system of graph structures corresponding to life systems. As for the equivalence formula (1), it simplifies this approach by "filtering out" those redundant graphs which do not correspond to any biological systems.

We can show that there exists a morphism from some biological graphs to the graph D above. Moreover such morphisms have biological meaning. For example, take the so called primordial graph from[5,6]. This graph expresses relationship between various functions of a hypothetical unicellular organism. We can construct the morphism in the following way. Functions of the Rashevsky graph C ("contact with food"), I ("ingestion"), FS ("food stimuli"), HS ("harmful stimuli"), I_{O2} ("intake of O_2") may be assigned the functions "reception", "decompositon", "reception", "reception", "reception" respectively, whereas to the functions C_B ("catabolic processes"), D ("digestion") and A ("absorption") of the Rashevsky graph one assigns the function "decomposition" of the graph D'. Whereas to the functions E ("energy excretion"), M_a ("ameboidal movement"), P_{CO2} ("production of CO_2"), S_B ("body synthesis"), I_t ("inner transport"), R ("reproduction"), T_P ("protoplasmatical transport"), S_{de} ("secretion of digestive enzymes"), D_{es} ("synthesis of digestive enzymes"), P_W ("production of waste") of the Rashevsky graph one assigns the function "synthesis" of the graph D'.

In a similar way, to the functions E_{CO2} ("excretion of CO_2"), D_{ef} ("excretion"), W ("excretion of waste products") can be assigned the function "excretion" of the graph D'. To the function E ("free energy") of the Rashevsky graph one assigns the "storage" function of the graph D'.

As another example let us show that there exists a morphism from the Chauvet graph[10], which expresses relationships between various systems of an organism, to the graph D'. The shape of the graph shows the morphism; more precisely, to the urinary system one assigns excretion, to the respiratory and cardiovascular systems – "reception"("assimilation"), to the digestive system – "decomposition", to the Nervous system – "control and regulation", and to the endocrine and blood system and tissues – "synthesis"(Figure 3).

Let us futher show that there exists a morphism from the graph of M. K. Babunashvili and B. S. Zilberfarb[11] to the graph D'. This graph shows how using hierarchy of the molecular organization of the cell and application of the functional homogeneity of the bioproduction, biological identification of the cellular metabolism with simultaneous partition of all biological productions into certain classes is performed (Figure 4). Let us construct a morphism from this graph into the graph D' in the following way. Let us assign the classes of biological productions of macromolecules, derivative biomolecules and bioconstruction blocks of the mentioned graph the function "synthesis" of the graph D', classes of biological production splitting the macromolecules, splitting the derivative biomolecules, splitting the construction blocks, as well as low-molecular predecessors – to the function "decomposition", decomposition products of the deriva-

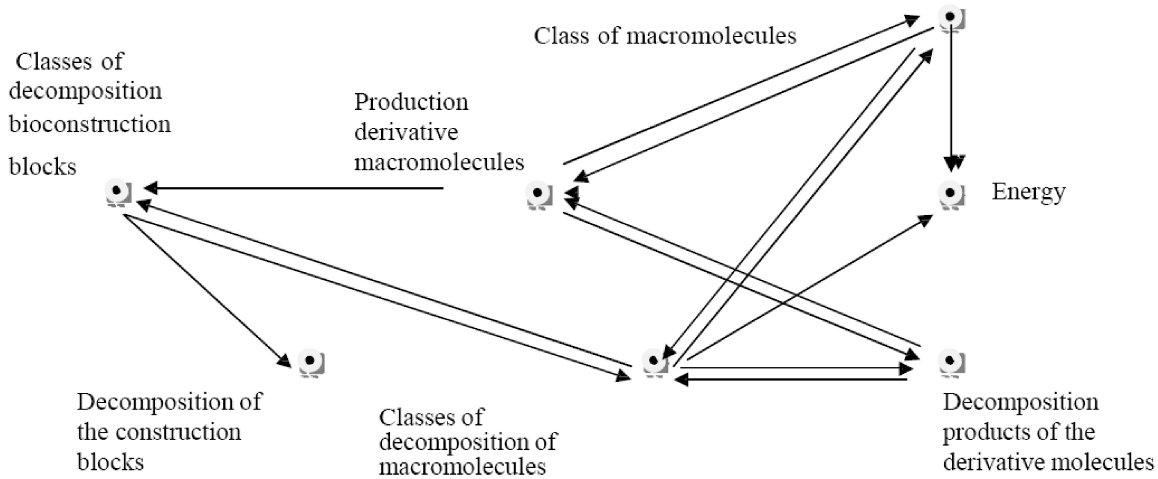

Figure 4 : The graph of Babunashvili-Zilberfarb

tive biomolecules – to the function “excretion”. Under the class of macromolecules in the graph of M. K. Babunashvili and B. S. Zilberfarb is understood that macromolecules are absorbed by the cell. Let us assign the macromolecules the function “reception”, whereas the energy – the function “storage”.

It follows that the graph D’ which, although represented in a simplified way, seems to be fully justified, whereas all biological graphs, if they are correctly constructed, are essentially similar. If there exists an epimorphism from the first graph to the second, this means that the first graph is more refined than the second. On the basis of the graph D’ one can construct more complicated and refined biological graphs.

Finally let us describe one more simple example of graph extension function as a first attempt to describe physical phenomena by our method. We will be concerned with the nuclear and Coulomb interactions in atoms. Consider a graph with the set of vertices V={p, n, e} (corresponding respectively to protons, neutrons and electrons in an atom).Let the set I of arrows of the graph correspond to various interactions (forces) acting between these, except for the gravitational interaction. Then a graph extension function can be constructed as follows:

$$f(p,i) \mapsto \{p,n,e\}$$
$$f(n,i) \mapsto \{p,n\}$$
$$f(e,i) \mapsto \{p\}$$

CONCLUSIONS

Arbitrary systems, will it be biological, physical, cybernetical, etc. may be described by a mathematical function, namely by a graph extension function, which we also call hierarchical function (and which mathematically shows hierarchical nature of science). This function can be also used to describe mathematical objects themselves, which in the paper is shown on the example of the action of the graph extension function on the set of integers. A new theory of graph extensions, similar to group extension theory, is outlined. A theorem about the equivalence of different extension functions is proved. There exists an isomorphism between the modified functional graph of the cell (functional block-scheme) and the morphological graph of the cell (the graph expressing topological membrane intertransformations of the cell) which expresses the most essential features of for the biology of the cell and captures one of the specific differences between living and non-living systems.

It is shown that the construction of the graph of a complex organism from the primordial graph given by Rashevsky is nothing but an extension of the primordial graph by the graph extension function.

It is described that there exist morphisms from biological graphs described by various authors to our functional graph. modified functional graph is valid biological graph.

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