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KNOWLEDGE PRODUCTION, HYPERBOLIC GROWTH AND PHASE TRANSITIONS IN BIOSYSTEMS

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ABSTRACT. – Knowledge Production, Hyperbolic Growth and Phase Transitions in Biosystems. The evolution of a global biological community such as the humanity or Earth's biota is shown to be directly connected with the production and accumulation [1]of valuable information (knowledge) needed for survival. Different ways of knowledge production based on the genetic, neuronal, and external memory types are considered. Common features of these memory types are indicated. It is proved that the growth of community population obeys a hyperbolic law. This law is verified using empirical data on the growth of taxonomic diversity of Earth's biota during the Phanerozoic, growth of human population during the late stage of anthropogenesis, and growth of the facilities of external memory for the last hundred years of the current informational epoch. We also assessed the moments of changing one dominant memory type into another during the evolution. It is shown that each transition leads to the emergence of a new dominant taxon with development rate three orders of magnitude faster than that before the transition.

Keywords: e*volution, information, biota, humanity, hyperbolic growth.*

1. INTRODUCTION

Complex systems, which we will consider here, are usually indicated by a large number of elements tightly organized among themselves. According to P. Teilhard de Chardin (1959) complexity depends "not only on the number and diversity of the elements included in each case, but at least as much on the number and correlative variety of the links formed between these elements". Evolutionary systems increase their complexity over time, so we should expect more complex objects to appear later in the evolutionary process (C. Bennett, 1990). R. Kurzweil (2005) outlined six epochs of complexity with domination of (1) physics and chemistry; (2) biology; (3) brains; (4) technology; (5) the merger of biology and technology; and (6) the whole universe. E. Steinhart (2008) showed in detail how Teilhard's vision of complexity harmonizes with the R. Kurzweil classification. Here we will consider from the informational viewpoint three of the epochs-based on biology, brains, and technology-placing the emphasis on knowledge production in biosystems (with technological components when necessary) and on different memory types, which are dominant in these epochs, as well as analyze transitions between them. We will try, as far as possible, to elucidate mechanisms of processes in memory and to make quantitative assessments of memory sizes and transition points.

An evolutionary biological community accumulates various information in common memory and uses it, via feedbacks, for solving tasks of survival. A system having memory and capable to solve tasks can generally be regarded as an intelligent one and therefore it can be

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called *civilization* meaning it in a broad sense. In the global scale, we can point two examples of such systems; these are: the human world system and the Earth's biota. It is of importance to clear how the accumulation of information influences the expansion of civilization. The hyperbolic growth is a manifestation of positive feedbacks in the interaction of system parts. For humanity these feedbacks are organized in the following loop: "…technological growth – growth of the upper limit of Earth's carrying capacity – demographic growth – more people, more potential inventors…" (A.V. Markov and A.V. A.V. Korotayev, 2009) and then the loop is closed returning to the same positions, but on a higher quantitative level.

In the case of biota, its diversity grows according to the following feedbacks: "more taxa – higher alpha-diversity… – communities become more complex and stable – extinction rate falls and/or emergence rate increases…" (A.V. Markov and A.V. Korotayev, 2009) and then the loop is closed.

The identity of growth law for human civilization and biota suggests an idea of the action in both cases of some universal mechanisms, bringing these distinctive systems to the same blow-up regime of growth. Indeed, in the above-mentioned loop for humanity the technological growth due to knowledge accumulation is the main driving factor as was shown by B.M. Dolgonosov and V. I. Naidenov (2006) and B.M. Dolgonosov (2009, 2010a, b). In the loop of biota, the decrease in extinction rate is evidence of the improvement of taxa fitness to ambient conditions and hence of rise in the amount of valuable information accumulated in genomes.

Thus, there are grounds to assume that similar informational mechanisms can regulate both human population and taxonomic diversity in biota. These mechanisms have recently been analyzed by B.M. Dolgonosov (2010a). Here we continue this analysis with the purpose to disclose mechanisms of informational processes and to consider key theoretical propositions in more detail.

The work is arranged as follows. In the beginning we discuss the question what is civilization from the informational standpoint and to what extent this understanding of civilization corresponds to the conventional notion of it. Further, we briefly consider the arrangement of memory as a basic attribute of civilization, characterize memory types and their function, and extract common features of memory. Special attention pays to the problem of information compression and to the interrelation between the total amount of information in memory and the amount of knowledge that represents small but vitally important part of information. We find a relationship between total memory size and population size, as well as dependence of knowledge production rate on population size. These dependencies allow us to deduce a law of population growth. Then, we touch the problem of biodiversity, determine a modified Shannon's entropy taking into account memory sizes of taxa, discuss the evolutionary essence of such factors as taxa memory sizes and knowledge production rates, which are macroscopic factors of the natural selection. Finally, we consider the transitions with changing dominant memory type as well as estimate the layout of transition points and the corresponding memory sizes.

The facts that compelled us to pay attention to this problem lie, it would seem, far from the informational issues; these are the data on human population growth for the last two thousands of years. H. Foerster et al. (1960) revealed that the population growth dynamics are described by a hyperbolic time-dependence of $N \sim (t_1 - t)^{-\alpha}$ with an exponent $\alpha = 0.99$ (where N is the population size, and t_1 is a singularity moment). Later, this law was slightly modified by S. Hoerner (1975), who put the exponent equal to unity, and this modification was then assumed as a basis in the subsequent works of different authors.

It has turned out that a similar hyperbolic law is also typical for the growth of biodiversity determining by the number of families and genera (A.V. Markov and A.V. Korotayev, 2007, 2008, 2009). These works analyzed the number of taxa in the marine and continental biota during the Phanerozoic lasted 542 millions of years.

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2. INFORMATIONAL TRAITS OF CIVILIZATION

In the philosophical literature the term *civilization* has different interpretations (e.g. A. Schweitzer, 1923; E. Benveniste, 1971; R. G. Collingwood, 1992). One of them describes the subject and, abstracting from details, it can concisely be formulated as follows: *civilization is a self-developing social system.*

Another interpretation gives a characteristic of such a social system, specifying the direction of its development, namely: *civilization is characterized by growing the socio-cultural level moving it away from the barbarian state.* It makes, in essence, more precise definition of the word *self-developing*, present in the first interpretation.

Depending on the scale of processes, we can consider the world civilization, involving the entire humanity, and local civilizations of different scales, which differ by territorial and socio-cultural features such as religion, language, phenotype, etc.

The development of civilization is associated with the accumulation of knowledge on the nature and society, with creation of new technologies, and with development of ethics and culture. As was noted by N. N. Moiseev (1998), "the collective intelligence … plays a role similar to the role that human mind plays in organism, that is, assists in the development of society and in the overcoming of permanently increasing challenges".

At the same time," the culture and technological grounds of living – these are still not a civilization. These are only constituents of civilization. As a basis of civilization identity I would rather mark out the identity of spiritual worlds. I think that it is the identity that gives rise to the unity of action" (N. N. Moiseev 1998).

This statement has something in common with the views of A. Schweitzer, who noted that there are two opinions concerning the nature of civilization: one considers civilization as a purely material entity, and another joins together the material and the ethical origins. A. Schweitzer (1923) has defined civilization (in the sense of the direction of development) as follows: "It is the sum total of all progress made by man in every sphere of action and from every point of view in so far as the progress helps towards the spiritual perfecting of individuals as the progress of all progress".

Meanwhile, both the material and the ethical can be consolidated in **the concept of knowledge**. This consolidation is quite natural because knowledge can involve the essentials of material objects and processes that are necessary *for adaptation to the surrounding world*, as well as the ethical norms helping in the spiritual perfecting of humans that is of importance *for self-organization of society*. These two essences of civilization are strong correlated, so a disbalance between them inevitably retards the progress compelling to develop the retarding essence and thereby restoring equilibrium (apparently, seldom short-term breakthroughs in the sphere of spiritual alternate with long-term periods of lagging in this sphere and dominating of the material origin). The presence of this correlation between different constituents of knowledge allows us to adopt *the total amount of knowledge (material and ethical) as an indicator of the developmental level of civilization*.

Thus, *from the informational viewpoint, civilization represents a multicomponent system having memory and producing knowledge necessary for survival.* This definition of civilization does not contradict the conventional notion, although broadens this concept on systems of not only humanitarian nature but also on the biota, because the presence of memory and a processor (or rather a multiprocessor consisting of many processors allocated over the whole memory) closely connected with memory, is typical both for humans and for other biological species. There is no contradiction here with the modern understanding of biota and its evolution, because: "the Earth's life evolves not like a set of uncoordinated objects (organisms, species, or populations) each of which is anxious for their own survival and must rely upon itself only. The life develops like a single whole. 'Modular assembly', information exchange, cooperation, and symbiosis – here is the basement for the development of life from very first its steps on the Earth" (A.V. Markov, 2010).

The above-introduced concept of civilization is a special case of informational systems. Generally, an informational system is defined as a system “which is capable to (i) perceive, (ii) store, and (iii) generate macroinformation” (D. S. Chernavsky, 2004).

The peculiarity of civilization is that it is obliged to produce *vital information* in order to provide its own existence, while macroinformation has a more general sense and is not necessarily directed to the solution of life-support tasks.

In the concept of civilization there are two key notions; these are: **memory** and **knowledge**. We understand knowledge as conditional information generated in the course of analysis of the perceived unconditional information received as signals from the world. The conditional information is valuable (useful, vital) information, which is extracted from the perceived information. Methods of extraction (or data processing methods) also represent an important part of knowledge, and the process of extraction represents the knowledge production of which we have mentioned in the definition. This understanding of knowledge has common features with the scientific (and maybe artistic) method of cognition of the world: “scientific work in the field of natural sciences includes two necessary elements: perception of unconditional information from the nature and generation of conditional (theoretical) information” (D. S. Chernavsky, 2004).

In respect of memory it is known that there are three types of it: genetic, neuronal, and external. The first two types are internal for biological subjects constituting civilization. Another matter is the external memory – its carriers are objects external for subjects of civilization. Developed external memory is an exclusive attribute of the modern human civilization, where this type is realized as different external information carriers: physical specimens, books, different magnetic and optical carriers, etc. Genetic memory dominates in biota, providing accumulation of valuable information and its inheritance. Thus, biota demonstrates the above formulated features of civilization, which can be named the biological one. Human civilization grown from the biological one uses advantages of the neuronal memory which has perhaps reached, on a definite stage of anthropogenesis, the size of genetic memory and then surpassed it providing an accelerated development of the human phyletic branch. The further development of humanity results in the enhancement of external memory, which (as we show below) has recently become dominant due to the fast improvement of computer carriers.

Undoubtedly, the domination of one or another type of memory must influence the type of civilization and the rate of its development. So it is important to analyze the arrangement and mechanisms of working different types of memory.

3. AN OVERVIEW OF MEMORY TYPES

The assignment of memory of any type is to reflect structures and processes in the world onto internal patterns of memory. For this purpose memory must have a set of elements and facilities for establishing links between them as well as, in addition, the rate of pattern formation must be sufficient for adaptation. If memory contains N elements and each element has n states, then the total number of memory states will be equal to n^N and the maximum memory capacity will be $N \log_2 n$ bits. Thus, at a fixed n, memory size is completely determined by the number of elements N. Earlier B.M. Dolgonosov and V.I. Naidenov (2006) and B.M. Dolgonosov (2009, 2010b) have estimated the amount of valuable information accumulated in memory. Below, we give an estimate of the base memory size by the number of elements, but without taking into account both various structures and the hierarchical operational superstructure that significantly increase memory size (it is yet impossible to estimate this contribution). We outline the memory functioning and mark out some universal mechanisms of information processing, intrinsic to various memory types.

3. 1. Genetic memory mechanisms

Elementary units of this memory type are base pairs in genome. Eukaryotes have additional mechanisms of encoding information based on complex hierarchical structures in which along with DNA there take part RNA, proteins, and different chemical groups modifying nucleotides and aminoacids. It has not yet clear how to assess memory size of such a complex organized system. This inclines us to use a simplified way taking into account only genomic nucleotides. But even in this case, the assessment of memory size is not so simple because of a rich structure arranged on a set of nucleotides. The structure includes numerous links between local formations whose combinations allow encoding valuable information on the structure and function of organism. Indeed, the exon-intron structure of genes enables to combine separate elements in gene formation (by means of duplication, transposition, and shuffling). As a result there appear new genes that encode different proteins using different combinations of exons and introns of the same gene. It was shown that there is a correspondence between gene exons and domains of proteins encoded by these genes. Although introns do not encode proteins, they are not a quite inert material because they include large amount of various regulatory elements affecting gene expression.

The formation of gene ensembles governed by single genes – transcription activators – plays an important role (R. Tupler et al., 2001; A.V. Spirov et al., 2002). This way allows generating large assortment of proteins on relatively small gene numbers. At the same time, less than 1.5 % of human chromosomal DNA take part in encoding proteins. In addition to protein-encoding genes, there are genes whose end product is RNA. Families of genes, formed through duplication, diverge in time. Some of them accumulating mutations are converted to pseudogenes, which are incapable to encode proteins and RNA. Pseudogenes are formed also due to splicing and reverse transcription.

Regulatory functions are performed by means of gene networks responsible, in particular, for phenotypical traits of organism. A gene network is a group of coordinatively functioning genes consisting of (a) a central regulator of the protein or nucleic origin; (b) a group of genes (cassette) containing, in their regulatory regions, sites of binding the central regulator that provides the coordination of expression of cassette genes; and (c) signal transmission pathways from the world through a receptor to the central regulator. The presence of multiple binding sites provides high combinatorial capacity of code (hence, large memory size) that enables genetic programs to significantly build up their complexity without essential growth of genome sizes. An additional possibility for memory size growth is provided by an increase in the number of hierarchical regulatory levels of gene networks when passing from prokaryotes (with two levels: transcription and translation) to eukaryotes (with six additional levels) (N. A. Kolchanov et al., 2002a, b). The presence of such diverse structures and ways of encoding information means that not only base pairs contribute to the memory, but also many structures of different hierarchical levels.

It can be expected that organism complexity is directly correlated with the amount of valuable information accumulated in genome. If so, we can order groups of organisms by their non-redundant genome sizes. It is difficult to directly determine these sizes; therefore A.V.

Markov and A.V. Korotayev (2009) proposed to consider this problem in a comparative aspect for specifically selected groups of organisms using the following rules: each group is *monophyletically complete*, i.e. originates from the same ancestor and involves all descendants of this ancestor; the groups are ordered chronologically – by their emergence moments; an earlier group includes the later one; in each group the species with minimum genome size is found.

This minimum genome size is regarded as an estimate of the size of non-redundant genome for a given group. The above-listed rules allowed the authors of the cited work to construct the following chain of embedded taxa: all living > eukaryotes > animals > chordates > vertebrates > tetrapods > amniotes > mammals > primates, and to indicate, in each taxon, the species with minimum genome size. Juxtaposing the minimum genome size with the taxon emergence moment, we can trace the growth of minimum genome during the evolution of Earth's biota (Fig. 1). It turns out that during the long period from the beginnings of life on the Earth to the emergence of mammals in the late Trias (about 220 millions of years ago) the minimum genome grows according to the hyperbolic law $Y = C(t_1 - t)^{-\alpha}$ with parameters $C = 2.03 \times 10^9$, $\alpha = 2.55$, $t_1 = 0$ (determination coefficient $R^2 = 0.965$), where Y is the minimum genome size (millions of base pairs); t is time (millions of years ago). The singularity moment t_1 was fixed at zero that means it falls into our time. Even if it is not so, the parameters change a little. For example, at the displacement of t_1 on ± 50 millions of years the exponent α shifts on ± 0.17 relative to the above value, the constant C gets values of 7.84×10^9 and 0.47×10^9 respectively, but R^2 changes insignificantly, in the 4th decimal digit. Note that the above-mentioned authors found distinct values: $C = 0.16 \times 10^9$, $\alpha = 2$, and $t_1 = 85$ with a minor value of $R^2 = 0.959$ (A.V. Markov and A.V. Korotayev, 2009).

As seen from Fig. 1, with the emergence of mammals the further growth of genomes becomes inefficient and is frozen at a level of ~2 billions of base pairs (underline that this is an estimate for minimum genomes), and the subsequent growth of genetic memory is provided with a more efficient collection of "combinatorial mechanisms of the regulation of transcription and exon-intron structure, mechanisms of alternative splicing, and epigenetic mechanisms, hereby creating the grounds for an exclusively efficient way of encoding vast diversity of variants of the same protein… This is an evolutionary adaptation of wide ability, allowing eukaryotes practically unlimitedly to build up the complexity of genetic programs of individual gene expression without an appreciable increase in genome sizes" (N.A. Kolchanov and V.V. Suslov, 2006).

So, in spite of the freeze of genome growth, a rise in memory size goes on along with increasing complexity of organisms but already using other mechanisms. This can be depicted by extrapolating the observed trend to the region of genome size stagnation (Fig. 1). This extrapolation shows to what extent genome must increase in its size to provide the appropriate growth of memory. As was noted by N.A. Kolchanov et al. (2002a, b), the additional encoding mechanisms developed in eukaryotes allow the memory to increase its capacity to the level that would require the increase of genome size to $10^{10} - 10^{11}$ base pairs that corresponds to a 10–100-fold increase.

In human genome there are about 5 % of encoding and regulatory genes (this is the non-redundant DNA), and of this quantity it turns out to be sufficient to build organism, or more exactly to set a spectrum of possible pathways of its building, but what a pathway will be realized, it depends on specific environmental conditions that affect the organism (A.V. Markov, 2010).

More than 95 % of genome have no direct relation to genes and encode neither proteins nor RNA (C. Adami et al., 2000; E. S. Lander et al., 2001; A. M. Lesk, 2002; L. D. Stein, 2004; A. A. Sharov, 2006). This is the so called "junk DNA", which cannot nevertheless be regarded as genetically inert because it contains mobile genetic elements, in particular, transposons promoting different innovations in genome. Due to their relocations, they can modify available genes, produce new genes, and cause mutations including significant chromosomal reconstructions. Not less than 80 % of mutations and reconstructions of DNA are the result of their activity (M.G. Kidwell, 2005). It is possible that non-coding sequences, prevailing in eukaryotic genomes, nevertheless encode something not requiring the conventional triplet code. Otherwise, they would degenerate into random sequences, which are eliminated by the selection as it occurs for prokaryotes (I. B. Rogozin et al., 2002). Summarizing, we may conclude that the "junk DNA" supports necessary diversity in the variability of genome, and the natural selection culls out harmful mutations. This accelerates the production of vital information providing adaptation to the environment variability. Thus, "junk DNA" may be interpreted as auxiliary (partially processed) information, which can, in good opportunity, be needed for producing vital information.

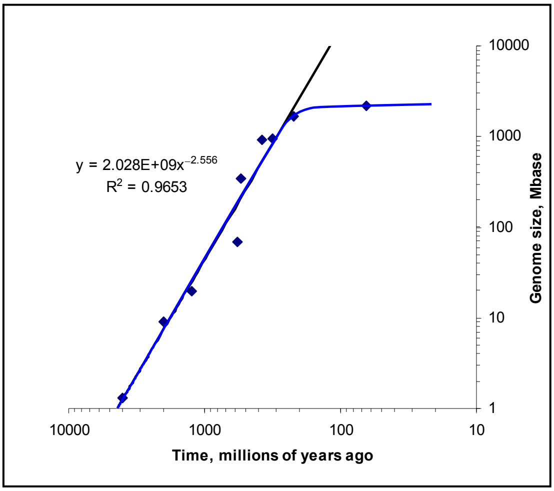

Fig. 1. Minimum genome size growth during the evolution of life. Markers indicate taxa minimum genomes sizes versus taxa emergence moments (data source: Markov and Korotayev, 2009).

Because of such a complex genome structure, the direct estimation of genome memory is difficult; it is possible only to count the number of elements in the total genetic memory of humanity.

Taking into account a human genome size of 3200–3300 Mbase and the current human population slightly less that 6.9 billions (see data of the US Bureau of the Census, http://www.census.gov/ipc/www/idb/worldpopinfo.php), we find the number of elements, 2×10^{19} base pairs, in the total genetic memory of humanity. Memory size in bits can be determined from this value by multiplication by $\log_2 n = 2$ (since there are four types of nucleotides, $n = 4$) that gives 4×10^{19} bits.

From all the information stored in genome the part of vital information (encoding and regulating) depends on genome size. For example, unlike the human genome with a 5 % non-redundant part, relatively small genomes of prokaryotes of sizes within the range $10^{-1} - 10^{1}$ Mbase (although sometimes there are bigger genomes – see: http://www.ncbi.nlm.nih.gov/genomes/lproks.cgi?view=1) have the non-redundant part up to half of the genome (sometimes to 80 %), and the rest is related to the "junk" part.

Thus, in spite of the different value of information in genome, we can state that *genome contains extremely compressed information compared to the information that is required to describe the organism built by this genome*. Such a compression has required billions of years of the evolution of life (from auto-catalytic cycles to the RNA world and then to the world of DNA–RNA–protein) (S. Kauffman, 1990), when a reliable way of encoding information was found, and on this basis viable codes were selected from a variety of generated codes.

A mathematical analogy of this process, although having a much less degree of compression, is the construction of **an axiomatic theory** in which a branched network of theorems is deduced from a small set of axioms. If the theory is considered as a whole, the amount of information (text) will be impressive enough. But if we retain only the formulations of already proved theorems (that are much shorter than proofs) but remove the proofs themselves, then significant compression of information can be achieved. In the vein of this analogy, *genome can be regarded as a set of formulations of the theorems proved during the evolution. In essence, their proving is constructing viable organisms on the basis of the genome* – an exclusively complex process, the description of which on the molecular level would form a text of vast size. But if theorems are formulated with mistakes (or genome contains fatal errors), these theorems cannot be proved (accordingly, organisms built by this genome are nonviable). From the said it follows that genome contains the information compressed over all the preceding evolution of life.

3. 2. Neuronal memory mechanisms

Main operational elements of this memory type are neurons. They are interconnected with axons, forming synaptic membranes at the places of contacts. A neuron can be in the active or passive state that depends on properties of synaptic membranes, varied under the action of mediators. Neurons are combined in ensembles (neuronal networks), basic types of which are genetically programmed but admit intravital modifications with the formation of new contacts between neurons. The information received from the world is saved in the form of neuronal ensembles (N. M. Grzywacz and P. Y. Burgi, 1998; H. A. Lechner et al., 1999). The addressing to information stored in memory provokes activation of separate neurons or neuronal ensembles.

Neuronal memory stores information of different degree of transformation, namely, sensory information and three types of processed information: primary, secondary, and tertiary. Sensory information occupies maximum memory volume. The transfer of information from the sensory level downward the hierarchy occurs mainly in two ways: semantic (by extracting abstract knowledge) and episodic (by storing sensations, emotions, associations, etc.) (J. R. Anderson, 1976).

The capacity of sensory memory is essentially larger than the primary one. A part of information from primary memory is substituted with newly received information, and another part transfers to the secondary memory, for example, via rehearsal. Secondary memory has larger capacity and duration of storage than the primary one. Unlike the primary memory, the secondary one is organized on the basis of the semantic value of information. Information from the primary memory is extracted with high speed, and from the secondary one, slower because of the necessity of retrieving different variants. Finally, the tertiary memory is characterized by firm fixation of the past experience and is extracted with high speed.

Brain represents a mosaic set of interacting neuronal elements – micro- and macrocolumns, which create associations and chains, permanently adapting their boundaries according to received signals. The signals are transformed and encoded into different sets of primary afferent fibers. Activities in these sets excite processes in different cortical regions. These spatially separated regions are connected by a widely branched distributional system. Neurons in separate nodes of this system are not projected into a kind of general convergent target in which a certain integrated thought (image, reflection) could be concentrated. This thought exists as a dynamic activity of the distributional system (V. B. Mountcastle, 1998). Thus, memory is an integrated property of brain activity that shows itself in interactions of different brain structures. Memory patterns have no definite location, but can be read from neurons of different brain structures. The topography of the functional subsystem responsible for reproduction of images changes from time to time (the so called phenomenon of walking active mnestic centers).

Thus, *in the neuronal memory (just like in the genetic one) there is differently processed information. The processing goes on permanently, accompanying with the transfer of processed and compressed information from the sensory memory to other forms of memory and providing thereby extraction and accumulation of valuable information.*

The transfer from the sensory memory towards the tertiary one is accompanied with compression of information. Using the prior analogy with an axiomatic theory (see subsection 3.1), it can be noted that only formulations of proved theorems finally remain in memory, i.e. manifold verified data, rules, images, notions – everything that forms a pattern of the world, whereas proofs themselves (including logical pathways brought to these representations) are often removed (forgotten) as useless because all these statements are already confirmed by personal life experience.

The amount of stored information depends on the number of neurons as well as on the abundance of links between them that can be formed as necessary. This circumstance complicates the calculation of the actual brain memory size varying during a life span. However, we can assess the number of neurons, which compose the basic memory size. It is known (F. Bloom et al., 1988; H. Haken, 1996; A. Ndabahaliye, 2002) that human brain consists of $\sim 10^{10} - 10^{11}$ neurons. This is an estimate by orders of magnitude, and in such a case the middle of the range should be found as the logarithmic mean; now it is equal to 3×10^{10} neurons. Hence, bearing in mind the present human population we find an average estimate of the neuronal memory of humanity of 2×10^{20} neurons (or bits if adopting that a neuron is able, by forming its own circuit, to encode one bit of information). Thus, at present the neuronal memory is 5 times more than the genetic one by the number of elements. As the accuracy of these estimates is not large, we may state only that the difference is half an order of magnitude.

Let us consider the question when the transition from the domination of genetic memory to that of neuronal one could happen. For this purpose we consider the growth of brain volume during anthropogenesis (Fig. 2) drawn from the paleo-anthropologic data collected by S.V. S. V. Drobyshevsky (2007). The growth mostly obeys a hyperbolic law of $Y = C(t_1 - t)^{-\alpha}$ with parameters $C = 1.90 \times 10^4$, $\alpha = 0.465$, $t_1 = 0$ ($R^2 = 0.800$), where Y is the brain volume (cm^3), t is time (thousands of years). The singularity moment t_1 is fixed at zero, i.e. it is assumed that it falls into our time. About 250–300 thousands of years ago, brain growth starts to decelerate and then goes into a plateau. This deceleration is conditioned by biomechanical problems such as child-bearing, load on backbone, and shift of gravity center, appearing as a result of brain growth. Nevertheless, memory size continues to increase due to the development of the cortex responsible for the formation of a hierarchical superstructure that allows creating neuronal networks and gives additional resources for storing information and working with it. So the trend depicted in Fig. 2 can be prolonged in the region, where brain does not grow. The prolongation shows to what extent brain volume should rise to ensure this growth of memory.

Brain volume of modern humans varies in wide limits: 1000–2000 cm^3, and in average is equal to 1350 cm^3. Brain volume of the hominid *Sahelanthropus* lived about 7 millions of years ago is estimated as 350 cm^3 (at an unknown range of variation), i.e. roughly 4 times less as compared with the modern humans average value. It means that the relative growth of brain during anthropogenesis is approximately half an order of magnitude like in the comparison of genetic and neuronal memory (remember that there was a 5-fold growth there, but in this case the difference between 4 and 5 is insignificant because of large uncertainty in the data).

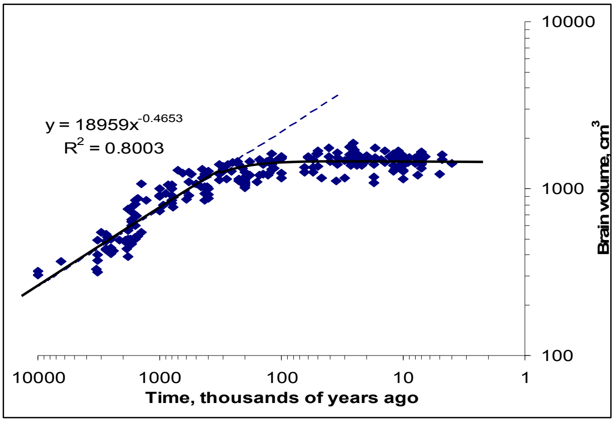

Fig. 2. Brain volume growth of fossil hominoids during anthropogenesis (data source: Drobyshevsky, 2007 (table 3).

These estimates allow assuming that the transition took place likely about 7 millions of years ago. Because the genome size of $\sim 10^9$ base pairs weakly changed since then and the species-ancestor population was $\sim 10^5$ individuals, we can find an estimate of the total genetic memory of $\sim 10^{14}$ base pairs. Hence, at the transition moment, the same number of elements (by an order of magnitude) was in the total neuronal memory (fig. 3).

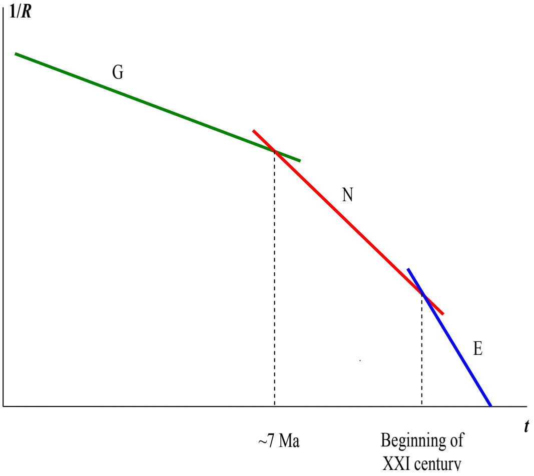

Fig. 3. A schematic time-dependence of the reciprocal total size of genetic (G), neuronal (N), and external (E) memory according to the equation $1/R = w(t_1 - t)$ with parameters presented in Table 1 for each memory type. The number of elements R in total memory size is estimated as $\sim 10^{14}$ and $\sim 10^{20}$ at the G–E and N–E transition moments, respectively.

The question rises, to what extent the approach based on the calculation of the number of memory elements is adequate. It would seem that this approach contradicts to the fact that brain of big mammals (e.g. elephants or whales) surpasses human brain and nevertheless populations of these species are not large compared to humans. To answer this question, we should account for two circumstances. The first is that we should consider the evolution of brain moving along a trajectory of development, i.e. along a phyletic branch, in our case, the phyletic branch of humans.

The second circumstance is associated with the fact that passing from the human phyletic branch to that for elephants or whales, we need to bear in mind the significant difference in body masses as well as the fact that there is a definite correlation between the masses of body and brain. With growing body mass, the peripheral nervous system also grows (roughly proportionally to body surface), and its servicing requires increasing the number of brain neurons proportionally to the power ~2/3 of body mass (E. Macphail, 1982).

That is why big brain still does not ensure fast growth of species population. It is important to underline that brain growth in the evolutionary process should be monitored along the phyletic branch of the species under study.

Returning to humans, note that anthropogenesis was accompanied with the development of neuronal processor that assists a deeper processing of received information. In its turn, the development of neuronal processor is connected with the enhancement of the means of social communications (E. Herrmann et al., 2007), which induce in due course the formation of the "cultural memory" and a developed language. During the evolution, appropriate morphological changes have occurred in brain, which are associated, in particular, with the development of cortex. In addition, it was needed to increase memory above the size that is necessary for servicing the peripheral nervous system to be able to allocate a more developed processor (rather a multiprocessor distributed over all the brain volume and operating in parallel) along with sensory information (as the initial material for its operation) and variously processed information. The progressive growth of neuronal memory has finally led to the situation when it surpassed genetic memory by the number of elements. To all appearance, just this has occurred in the anthropogenesis and ensured the accelerated growth of population. Thus, in this context the number of memory elements is of importance for accumulating knowledge and growing species population.

3. 3. External memory mechanisms

This type of memory includes carriers of different types, but computer carriers such as magnetic and optical disks, flash memory, etc. predominate. Information on these carriers is organized by means of file systems. A file system is unnecessarily directly associated with its physical carrier; it can be virtual or networking and can operate with information allocated over different carriers, sometimes remote from each other on large distances. Every carrier is divided into clusters. A single file can be allocated over several clusters disposed in different places of the carrier. Clusters and files are arranged by drivers of operational system, which form a network governing multiple files. Information can be duplicated and rewritten in various places of the same carrier or on different carriers, changing the physical location of information. Judging by the above description of genetic and neuronal memory, something alike there is also in the external memory that hampers searching the places where needed information can be located (remind that such a fragmentation can be associated with duplication, transposition, and shuffling of exons and introns in genome; and with walking of mnestic centers in brain).

Information can be characterized by its social significance and potential value. Significant information is duplicated many times, and in this connection we can introduce frequencies of occurrence of individual informational objects. However, the frequencies are not always directly connected with the potential value from the standpoint of community survival. Vital information is commonly scattered over different informational objects, so it is hard to extract it from the context and calculate its total amount. But even if it would be able to do this, simple summation of the sizes of extracted objects is all the same incorrect because the objects are non-equivalent. Thus, if to sum up the sizes, it is necessary to use weight coefficients evaluating information in the objects. It is commonly considered that the value of information can be defined through the reduction of uncertainty after receiving this information (D. S. Chernavsky, 2004). However, this approach implies the presence of a paradigm helping the information to be interpreted. But if the information is not built in the existing paradigm, its value cannot be determined (and what is more, at this moment it is equal to zero); its value can be revealed only in the future, in favorable concurrence of life circumstances.

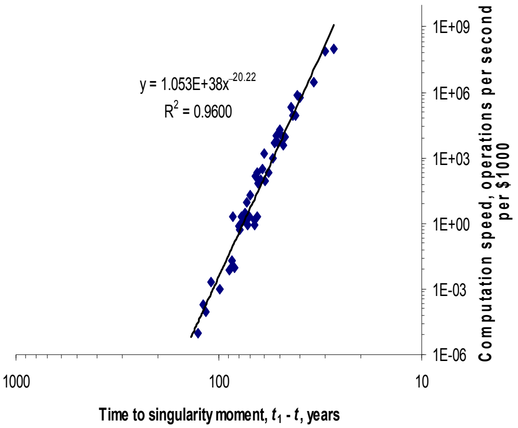

Fig. 4. Hyperbolic growth of computation speed (data source: R. Kurzweil, 2001). Singularity is achieved at the year $t_1 = 2027$.

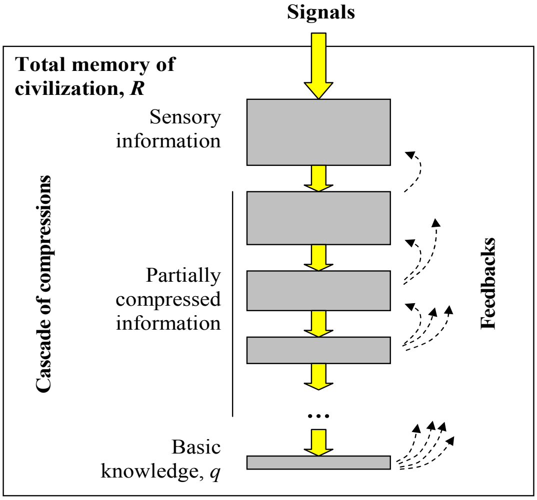

Fig. 5. A conceptual scheme of information flows in civilization. Signals from the world undergoes the cascade of compressions, where the top level is occupied with sensory information; the intermediate evels, with partially compressed information; and the bottom level, with basic knowledge. Dashed arrows denote feedbacks that control upper levels of memory.

There are also other difficulties in the accounting for the amount of valuable information, for example, connected with the use of different languages. First of all, the said concerns natural languages, which are poorly algorithmized. But even the application of solely algorithmic languages does not resolve the problem, since the description of the same informational object in different languages yields programs of different length, and to indicate the minimum length program is a problem algorithmically irresolvable (B. M. Kolmogorov, 1987, A. V. Melkikh, 2008). The same difficulties are characteristic of the approach of C. Bennett (1990), in which complexity (that is evidently proportional to the amount of information) is estimated via logical depth defined as the "execution time required to generate the object in question by a near-incompressible universal computer program, i.e., one not itself computable as output of a significantly more concise program" (C. Bennett, 1990). That is why we have to deal with the total amount of information. As seen, the same situation takes place also for two other types of memory – genetic and neuronal.

Facilities of external memory can be assessed by the computational power defined as the number of operations in unit time per unit cost of hardware.

Treatment of the data represented by R. Kurzweil (2001) shows that during the whole XX century the computational power increased according to the hyperbolic law (Fig. 4) $Y = C(t_1 - t)^{-\alpha}$ with parameters $C = 1.05 \times 10^{38}$, $\alpha = 20.2$, $t_1 = 2027$ ($R^2 = 0.960$), where Y is the computational power achieved to the moment and measured in the number of operations per second per 1000 constant dollars of the year 2000, t is time (year)

Along with the power, the growth of stored information proceeds. As shown below (see section 6), a power law relationship between computational power and information stored (looking like $\dot{R} \sim R^2$, where R is the total amount of external memory) takes place, so the accumulation of information also will go on according to a hyperbolic law. The singularity moment is fixed at the year 2027 that coincides with the singularity moment for human population (see below section 4).

According to the data of the researchers from the University of Berkeley, California (How much information, 2003), the humanity in 2002 produced 5 exabytes = 5×10^{18} bytes = 0.4×10^{20} bits of information, a prevailing part of which (92 %) was stored on magnetic carriers, mostly in hard disks (these 5 exabytes are less than one third of the new information that is communicated through electronic information flows – telephone, radio and TV, and the Internet – being circa 17.7 exabytes). Bearing in mind the information stored for all years till the moment, we can obtain an estimate of the current size of external memory: $\sim 10^{21}$ bits. These findings most likely underestimate the real situation, because the production of carriers has grown rapidly for the last years and the capacity of some carriers has already reached several terabytes. Of course, a prevailing part of external memory is filled with repeatedly used information such as films, music, texts, pictures, etc., as well as sensory information of private character, e.g. photographs, video and audio tracks (we imply simple fixation of surrounding events). This information flow contains very little of unique, vital information. In any case, it is clear that at present the external memory has already surpassed markedly the neuronal one. The transition occurred quite recently, at the turn of XX–XXI centuries (Fig. 3) and brought to the important quantitative change: *if earlier the total memory size of civilization grew proportionally to its population (because memory was internal for subjects of civilization), then now the domination of external memory makes population growth non-obligatory for further increasing memory as this can be done due to external carriers.*

3. 4. Common features of memory

In spite of that various memory types are grounded on a distinct elemental base and use different mechanisms of storing and processing information, there are some common traits independent of specific realization. First of all, this is the fragmentation of valuable information over all volume of memory, ambiguity of the mapping of real objects and processes onto memory patterns, diverse ways of encoding information depending on language used and on life history. It is necessary to account for language redundancy, duplication of fragments, errors of coding, reserve of passive structures and so on. These factors are urgent for any memory type. So, the size of information stored cannot be estimated quite definitely and it is impossible to indicate the minimum memory size needed to store valuable information. But it is possible to compress the perceiving information step by step using two ways: first, revealing regularities in the data organization and, second, removing the information that seems to be insignificant. The purpose is to produce knowledge (vital information) that is performed through: extracting valuable information, compressing it as much as possible, and encoding it in memory. This can be done by the construction of algorithms describing technologies, methods, theories, rules of behavior and so on. The compression is a process expensive by energy and time and therefore is performed only under vital necessity.

Since the value of information depends on circumstances, it is necessary to have a reserve of memory to store not only vital information needed at the moment but also the information that can be needed in the future. Bear in mind that the production of new valuable information is a long-term process that includes searching regularities in the data structure, ignoring insignificant details, and compressing information. So, during all this process there is a need to store in memory intermediate information, which is not still compressed enough, but further compression is unprofitable for the moment because of large expenditures of resources.

Thus, memory includes information on different stages of transformation, from the initial information (perceived signals) to vital information whose degree of compression is determined by the current state of the system of knowledge. The development of this system promotes further compression of information. A conceptual scheme of information flows in civilization is shown on Fig. 5. Here following S. N. Nielsen (2007) we can see three major types of information that play a part in determining the complexity level of the system, one belonging to the components (boxes), one stemming from the flows (area arrows) and one from the system controls through feedbacks (dashed arrows). The feedbacks represent the ascendency in the system that is necessary for its self-organization.

It is known that: “systems with either vanishingly small ascendency or insignificant reserves [of flexibility] are destined to perish before long. A system lacking ascendency has neither the extent of activity nor the internal organization needed to survive. By contrast, systems that are so tightly constrained and honed to a particular environment appear ‘brittle’ in the sense of C.S. Holling (1986) or ‘senescent’ in the sense of S. N. Salthe (1993) and are prone to collapse in the face of even minor novel disturbances” (R. E. Ulanowicz et al., 2009).

3. 5. Fractal structure of knowledge

Memory of civilization grows along with knowledge amount. *Knowledge is not consolidated in memory, but, on the contrary, forms a set of rare, accidentally allocated, unconnected inclusions.* This statement is well exemplified by the allocation of exons in eukaryotic genome, which are randomly scattered and separated from each other with big introns. Another example is the brain zones responsible for various images that are randomly allocated in brain. Finally, the fact that files can be fragmented over many computer carriers and there is a small fraction of valuable information among them gives one more illustration of the above statement. The aforesaid concerns not only single memory carriers (single gene, brain, or computer), but, to a more considerable extent, to the whole memory of civilization, which is fragmentary by itself because consists of large number of carriers. As a result, randomness and fragmentariness in allocation of knowledge over all memory volume become more expressed. These features of memory allow representing knowledge in the form of fractal object consisting of unconnected parts (physically unconnected, but connected by networks). A mathematical analogue of such an object is known as **the Cantor dust** (e.g. B. B. Mandelbrot, 1982), whose fractal dimension is less than unity. From the above-mentioned it follows that the memory size q occupied with knowledge interrelates with the civilization total memory size R by a power law relationship $q \sim R^{\varepsilon}$ typical for fractals, where ε is the fractal dimension, which for a disconnected object (like the Cantor dust) is less than unity. Moreover, taking into account that knowledge occupies very small volume of memory (i.e. $q << R$) as well as that a set of inclusions in memory is a quite sparse fractal object, it should be expected that its fractal dimension is very small: $\varepsilon << 1$.

Of the exponent ε we can judge by the following example from statistical physics. The complete microscopic description of a system of N particles requires knowing $R = 6N$ values of particle coordinates and velocities. Passing to a macroscopic description, a small set of macrovariables like temperature, pressure, volume, number of particles and so on is needed, i.e. q encompasses 3–5 values, seldom more. At $N \sim 10^{23}$ the transition from micro- to macrodescription is evidently accompanied with enormous compression of information with the exponent $\varepsilon \approx \ln q / \ln R \sim 10^{-2}$ (supposing that a proportionality coefficient, not written out but implied in the formula $q \sim R^{\varepsilon}$, has a value of unity by an order of magnitude).

3. 6. Logarithmic compression of information

At the so small value of ε, the power law dependence $q \sim R^{\varepsilon}$ is close to a logarithmic one in a wide range of variation of variables. Indeed, writing the stated dependence in the differential form $dq \sim dR / R^{1-\varepsilon}$ and taking a limit $\varepsilon \to 0$, we get $dq \sim dR / R$ and after integration $q \sim \ln R$. Hence, *the amount of vital information grows logarithmically with increasing the total memory size.* This evidences a very strong compression of the initial information. Probably, the so strong compression is characteristic also for the evolutionary process in which natural selection extracts from the large amount of perceived information only the vital one and encodes it.

Taking into account physical units of the quantities q and R, the obtained logarithmic law of compression information should be written in the form $q = q_c \ln(R / R_0)$, where q_c is a constant, specific for the memory type used, and R_0 is the minimum memory size at $q \to 0$. Note that when domination of some memory type is the case, the amount of knowledge q can be measured in the q_c units, and R, in the R_0 units (i.e. we put formally $q_c = 1$ and $R_0 = 1$), then the information compression law takes a simple form of:

$$q = \ln R .$$

It can be interpreted by the following way: at the knowledge level q civilization is capable to recognize information received from the world in the amount $R = e^q$, i.e. figuratively speaking, *the scope of civilization exponentially increases with knowledge.*

Information and knowledge are accumulated in memory and used for recognizing signals and choosing behavior. As shown above, the inequality $R >> q$ holds true; it implies that among all information accumulated in memory knowledge occupies only a small part, whereas the most part of memory is filled with unprocessed or partially processed (intermediate, raw) information, which has still being transformed into knowledge (Fig. 5). This statement concerns any type of memory provided that not a single memory carrier (for which significant deviations from this rule are possible) is considered but all the carriers constituting the civilization.

4. THE NATURE OF HYPERBOLIC GROWTH

4. 1. Knowledge and the population size

All the long-term evolution preceded the information explosion of the last decades is characterized by the domination of the internal memory, whose size R is composed of the memory sizes of N separate subjects constituting the civilization; this yields the relationship $R = mN$. Let R_0 be an initial memory size when the civilization was in an incipient state and had a population size of N_0. Then $R_0 = mN_0$, $m = R_0 / N_0$, and $R = R_0 N / N_0$. Recalling that $R = R_0 \exp(q / q_c)$, we find $N = N_0 \exp(q / q_c)$. In the relative units (i.e. putting $q_c = 1$ and $R_0 = 1$) we can write: $N = N_0 e^q$.

It means that in the course of evolution not only the amount of recognized information, but also *the population size grows exponentially with accumulating knowledge*. This can also be interpreted in such a manner: a system with storing information includes positive feedbacks, which makes the system unstable. In other words, the emergence of new knowledge destabilizes the system and leads to significant changes in it. With respect to the genetic memory, this effect has recently been noted by A.V. Markov (2010): “small variations in regulatory genes can lead to large evolutionary transformations, including the emergence of new properties and functions, and to a general complexification of the living system”.

4. 2. A mathematical mechanism of the loss of stability

Let us consider a potential dynamic system with several stable states and with parameters drifting in time. The system is described by an equation $\dot{x} = -V'(x)$, where the over dot symbol denotes the time derivative, the prime denotes the argument derivative, x is a generalized coordinate (for example, population size), $V(x)$ is a potential. Equilibrium points of the system are found from the equation $V'(x) = 0$. Let the system have two potential wells separated with a potential barrier. In this case, the potential has three equilibrium points $x_1 < x_2 < x_3$, two of which x_1 and x_3 are stable (they correspond to the two wells) and one x_2 unstable (it corresponds to the barrier). From this it follows that $V'(x) = k(x - x_1)(x - x_2)(x - x_3)$, where $k > 0$.

Let the potential parameters change in time so that the potential well x_1 disappears. At the moment of disappearance, the points x_1 and x_2 merge with one another: $x_1 = x_2$ (Fig. 6), and the derivative of potential is transformed into $V'(x) = k(x - x_1)^2 (x - x_3)$. Denoting the deviation from x_1 as $y = x - x_1$ and the distance between x_1 and as $a = x_3 - x_1 > 0$, we can rewrite the equation $\dot{x} = -V'(x)$ in the form $\dot{y} = ky^2(a - y)$.

At sufficiently small deviations $y << a$, the latter equation can approximately be represented as $\dot{y} \approx kay^2$. This equation yields a hyperbolic growth of deviation. As approaching to the point $y = a$, this law is violated. Thus, *from the mathematical viewpoint, the hyperbolic law arises from the loss of equilibrium and is accompanied with the movement of the system to another, remote equilibrium state.*

In respect to the growth of population, the first potential well lies at the point $x_1 = 0$, where the population is extinct (or, at least, presents in an incipient state), and the second potential well at x_3 corresponds to a stable, non-zero population. The variable x is the population size N, the parameter a is the environmental carrying capacity, and ka is the coefficient of population growth w (see below). The convergence of the points x_1 and x_2 and the loss of stability of the zero potential well are caused by the appearance and development of memory and accumulation in it of valuable information, which allows the civilization to exit from the incipient state and to start building up its population size according to the hyperbolic law.

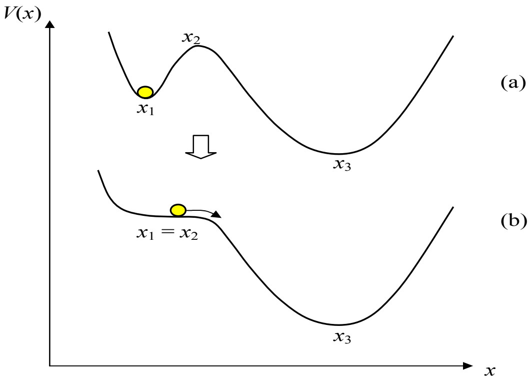

Fig. 6. Transformation of the system potential: (a) two potential wells x_1 and x_3 separated with a barrier x_2; (b) the loss of stability at $x_1 = x_2$ and the beginning of the transition to the stable state x_3.

4. 3. Knowledge production and hyperbolic law

The total rate of knowledge production is determined as the sum of contributions of separate subjects of civilization, therefore as a whole this rate is proportional to population size: $\dot{q} = wN$, where: w is a coefficient of population growth (another name is a specific information processing rate; its physical sense is the mean rate of knowledge production per subject, i.e. per capita for humanity or per taxon for biota). This is followed by the equation of knowledge production $\dot{q} = wN_0 e^q$, which can be rewritten in the form without parameters: $\ddot{q} = \dot{q}^2$. The process has a singularity point, at which all the key quantities such as the amount of knowledge q, rate of knowledge production $\dot{q}$, and population size N tend to infinity. However, growth rate of these quantities is significantly different depending on the distance to singularity point. Far from it, growth is slow, almost imperceptible, but in its neighborhood the process enters into the blow-up regime resembling an explosion. It is accompanied with increasing the accumulation of knowledge that results in accelerating the growth of population. Indeed, from the equation of knowledge production and the relationship $q = \ln(N / N_0)$ it is easy to derive an equation of population dynamics

$$\dot{N} = wN^2 .$$

Solving it, we obtain the well-known hyperbolic law of population growth

$$N = N_0 /(1 - wN_0 t) \text{, or}$$

$$N = w^{-1}(t_1 - t)^{-1} ,$$

containing the singularity moment $t_1 = 1/(wN_0)$. It is seen that the higher the specific processing rate w, the faster the population grows and the earlier the singularity moment is achieved.

Thus, it appears that *the hyperbolic growth first discovered empirically for human population* (H. Foerster et al., 1960) (Fig. 7) *and recently for biodiversity* (A.V. Markov and A.V. Korotayev, 2009) (Fig. 8) *has purely the informational nature. In principle, it must hold true for civilizations of any origin, in which properties of subjects – memory size m and information processing rate w – are constant, and the accumulation of information goes through the internal memory channels.*

4. 4. Drift of memory parameters

In reality, the memory parameters m and w change during the evolution. It is known that the last ~7 millions of years of anthropogenesis the brain volume has nearly 4 times increased (S.V. Drobyshevsky, 2007). The information processing rate has most likely increased too that is resulted from a complication of the hierarchical neuronal network in brain. However, on the background of the immense human population growth of 5 orders of magnitude (from 10^5 to almost 10^{10}), just a several times variation in these parameters gives only small relative deviation from the ideal case supposing the m and w to be constant. The admissibility of this idealization is caused by the fact that population size in the preceding epochs is known only within an order of magnitude; so its variation due to the drift of the parameters m and w lying within this range of uncertainty is quite acceptable.

To estimate how the drift of memory parameters distorts population growth dynamics, we consider a simplified situation assuming that these parameters linearly grow in time: $m = m_0(1 + kt/t_1)$, $w = w_0(1 + kt/t_1)$ (note that in reality the behavior of $m(t)$ is more complex – see: S.V. Drobyshevsky (2007), graph 83; however, the simple example under study is of importance for understanding how growth of m and w influences the population size). In this case the prior equation $\dot{N} = wN^2$ is modified into the equation $\dot{N} = wN^2 - (\dot{m}/m)N$. As noted above, during anthropogenesis there has been a 4-fold increase in brain volume (and hence in memory m) and most likely in the information processing rate w that corresponds to the coefficient $k = 3$ in the above formulae. Calculations using the modified equation with the linear drift of memory parameters at $k = 3$ demonstrate that population grows, as before, according to the hyperbolic law, but with a slightly shifted exponent value: instead of the prior -1 now we get -0.98, i.e. $N \sim (t_1 - t)^{-0.98}$. Strictly speaking, this exponent value is approximate – it works within some intermediate time interval. But the fact is that the modified hyperbolic dependence is an approximation of the exact solution of the task having the form $N = N_0 t_1{}^2 (t_1 + kt)^{-1}(t_1 - t)^{-1}$.

As noted in Introduction, H. Foerster et al. (1960) treating empirical data on human population have obtained the exponent -0.99, but not exactly -1. It is clear now that one of the possible reasons of this deviation can be the drift of memory parameters. Since deviation from the case with constant memory parameters is small, this idealized case can be used for an approximate estimation.

4. 5. Deviations from the hyperbolic growth

In respect of humanity, hyperbolic growth of population is caused by the domination of neuronal memory and the participation of the neuronal multiprocessor in knowledge production. H. Foerster et al. (1960) showed that the singularity moment t_1 falls into the end of 2026 (i.e. approximately t_1 = 2027) and found that the reciprocal knowledge production rate is w^{-1} = 200 billions of persons×years. Calculations of A.V. Markov and A.V. Korotayev (2009) using an updated demographic series yields the refined value w^{-1} = 215 billions of persons×years (fig. 7).

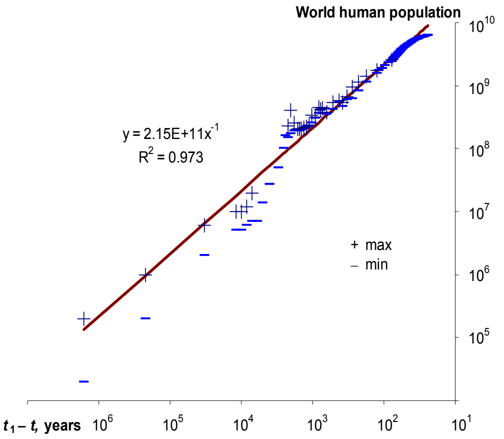

Fig. 7. Hyperbolic growth of world human population (data source: J. N. Biraben, 1979; S. Jones et al., 1994; see also data of the US Bureau of the Census: http://www.census.gov/ipc/www/idb/worldpopinfo.php). Singularity falls on the year t_1 = 2027.

It should be taken into account that hyperbolic growth of humanity describes the trend (long-term dynamics) of population smoothing short-term processes like cycles or fluctuations that result in deviations from the mean value. The mean value subsistence" (T. Malthus, 1826, part I.II.22). This thesis can be reformulated characterizes the stable population size that is ensured with the currently existing means of subsistence in accordance with the T. Malthus' thesis: "Population is necessarily limited by the means of as follows: "the growth of human population at a given moment of time is restricted by the top of Earth's carrying capacity being determined by the currently observed developmental level of vital technologies" (A. S. Malkov et al., 2007).

But the top of carrying capacity $N(t)$ just describes the long-term population trend, slowly changing with technological development, where t is the long-term (historical) time. At a given level of technologies the current human population $n(\tau)$ (where τ is a short-term, or local time) can significantly oscillate, faster than the technological development rate. This can be exemplified by Malthusian cycles: *excess of resources – fast population growth – exhaustion of resources – fast population decline*, as well as by epidemics and natural disasters. Natural and social reasons can deviate the population size from the carrying capacity upward or downward. After elimination of the reasons, the deviation relaxes to the level $N(t)$ according to the Verhulst equation $dn/d\tau = rn(1 - n/N(t))$: here $N(t)$ plays the role of the environmental carrying capacity, which slowly evolves with producing knowledge. *So, just the growth of $N(t)$ in the historical time scale displays the informational essence of civilization.*

5. BIODIVERSITY MACRODYNAMICS

5. 1. Entropy of a biological community

A biological community represents a complex system in which every subject behaves occasionally, so the whole community can be regarded as a statistical ensemble. Separate taxa are subsystems of the ensemble. If the state of a taxon is considered to be adequately described by its abundance, we can easily find the number of ensemble states $W = n!/(n_1!n_2!...n_N!)$, where N is the number of taxa, n_i is the *i*th taxon abundance, n is the community abundance, $n = n_1 + n_2 + ... + n_N$. Using Stirling's asymptotic formula for the factorials and finding the logarithm, we obtain an additive state function known as Shannon's entropy:

$$H = -\sum_{i=1}^{N} \frac{n_i}{n} \log_2 \frac{n_i}{n}.$$

This version of entropy can be called *populational entropy* emphasizing the fact that it is based on population abundances. Its maximum $H_{\max} = \log_2 N$ is achieved at equal abundances of taxa n_i = const. It is seen that the entropy maximum depends only on the number of taxa N. Shannon's entropy can be regarded as a measure of nonequilibrium or, more exactly, the difference $H_{\max} - H$ specifies the deviation of the community from its equilibrium state with maximum entropy. This measure of deviation has been used earlier by R. B. Evans et al. (1966) in the formulation of exergy and then developed by S. N. Nielsen (2007) in the semiotic analysis of ecosystems. On the other hand, in ecology the entropy is sometimes used as one of the measures of biodiversity along with the Kullback information measure, the exergy and others (S.E. Jørgensen and B. D. Fath, 2004; J. A. Camargo, 2008). N. Petrovskaya et al. (2006) applied these measures to a model community of three competitive species and showed that, in spite of the fact that all the species exhibit dynamically similar behavior, their contribution to the corresponding changes in the biodiversity measures is remarkably asymmetrical (emphasize that the matter concerns a nonequilibrium state).

Meanwhile, the above definition of entropy suffers from a grave shortcoming: *equilibrium abundances of taxa cannot in reality be equal to each other because of essential differences in their properties.* So, in calculations of the number of ensemble states we should be guided not by taxa abundances, but by a certain generalized characteristic, which in the equilibrium state tends to take the same value for every taxon. As further shown, the role of this characteristic is played by the taxon's memory size, which is of importance for the accumulation of valuable information necessary for survival. The question is how taxon's memory should be calculated: whether we need to take the total genome memory or only its non-redundant part.

To answer the question it is necessary to bear in mind that under constant ambient conditions the "junk" genome is not needed in principle (though then it would not be present in genome at all). But in reality the environment is subjected to significant changes, so there is a need to have an instrument providing variability of genome. This instrument is just located in the "junk" part in the form of mobile genetic elements. However, enlargement of this part of genome (for a reserve) is hampered by high energetic cost needed to replicate bigger DNA as well as to maintain and reproduce a variety of additional proteins resulting in growth of cell sizes. Therefore, there is a definite balance between the sizes of non-redundant and "junk" parts of genome, which depends, of course, on specific conditions of existence. In any case, it is clear that for its survival the taxon must have both parts of genome. It means that calculating the taxon memory size we should take into account the total genome memory. (Note that this conclusion has now seemed to be more reasonable than the prior suggestion to use only the non-redundant part of genome as containing the most valuable information – see: B.M. Dolgonosov, 2010b). At the same time, to order taxa by complexity and hence by the amount of stored *valuable* information we should use only the non-redundant part of genome that is what has been taken above – see subsection 3. 1.

As genome completely characterizes organism, it is naturally to think that the taxon state is described adequately by the mean genome size of organisms. Let μ_i be the mean size of genome in the *i*th taxon. The taxon's genetic memory is $m_i = \mu_i n_i$, and the total memory of all N taxa in the community is $R = m_1 + m_2 + ... + m_N$. The number of different states of the community regarding as a statistical ensemble is now $W = R!/(m_1!m_2!...m_N!)$. Passing to the asymptotics and taking the logarithm, we get Shannon's entropy in a new version:

$$H = -\sum_{i=1}^{N} \frac{m_i}{R} \log_2 \frac{m_i}{R},$$

which: can be named *memory entropy* contrary to the populational entropy written above. The above said about $H_{\max} - H$ as applied to the populational entropy is completely transferred to the memory entropy.

5. 2. Equilibrium community

In an equilibrium state, the memory entropy achieves its maximum $H_{\max} = \log_2 N$ the same as for the populational entropy, memory sizes of taxa equalize:

$$\mu_i n_i = m = \text{const},$$

and the community total memory becomes proportional to the taxa number $R = mN$. Thus, in a homeostatic state (i.e. close to equilibrium) the number N of viable taxa becomes again a key parameter of biodiversity, *but now this state is maintained not by equal abundances but by equal memory sizes of the coexisting taxa*. This conclusion is urgent for the biosphere, which usually stays in a homeostasis, except for seldom catastrophes disturbing it for a short while. Underline that *homeostasis does not mean lack of variability of ambient conditions, but only that this variability lies within definite limits, namely, does not result in fast and mass extinction of a great number of species*.

Note, by the way, that there is an interesting chemical analogy. A biological community resembles **a multiphase system** and there is the following correspondence between biological and chemical objects and quantities: taxa correspond to phases, the taxon memory m to the phase chemical potential, and the community total memory R to the thermodynamic potential of the system. It is known that in equilibrium chemical potentials of the coexisting phases equalize, and the same, as said above, occurs with the memory sizes of taxa.

The equalization of taxa memory sizes can also be explained as follows. The stability of a taxon correlates with its lifetime, which grows with accumulation of valuable information in memory because this increases the taxon's competitive ability. It means that memory size can be regarded as a macroscopic criterion of the natural selection. The taxa that lose competition for memory size to other members of community can go to extinction. As a result of this selection, memory sizes of the coexisting taxa tend to be equal. However, they cannot be exactly equal because of fast variations in ambient conditions, but equal only by orders of magnitude. *Such an equalization of memory sizes can be ensured not only by slow change in the genome size following the long-term trend in ambient conditions, but also by much a faster way – by the change in taxa abundances that compensates the underdevelopment of genome with higher abundance of the taxon.* After this equalization, the community total memory R will be proportional to the taxa number N in accordance with the above result $R = mN$.

5. 3. Hyperbolic growth

The maintenance by a taxon of its memory size on the community mean level is a necessary condition for survival but not a sufficient one. Permanent variations of ambient conditions require of organisms to elaborate adaptive reactions and, consequently, to continuously produce knowledge in the coexisting taxa, otherwise the competition will be lost. Hence, *evolutionary processes will equalize (by orders of magnitude) not only memory sizes but also rates of knowledge production over all taxa.* The rate of knowledge production depends on both valuable information accumulated in genome and the store of mobile genetic elements promoting acceleration of the process. As a result of the equalization of rates in different taxa, the total production of knowledge by the whole community will be equal to $\dot{q} = wN$, where w is the mean rate of knowledge production per taxon. Recalling the logarithmic law of information compression in producing knowledge $q = \ln R$ (compression occurs in encoding valuable information in genome), we obtain the same laws for knowledge production rate $\dot{q} \sim e^q$, the taxa number growth rate $\dot{N} = wN^2$, and the hyperbolic time-dependence of the taxa number $N = w^{-1}(t_1 - t)^{-1}$ as in the case of humanity, but with distinct values of parameters. If taxa are genera (evolution of the genera number is shown on Fig. 8), then parameter values for the Phanerozoic biota are: $w^{-1} = 4.34 \times 10^5$ taxa × million years and $t_1 = 30$ million years ($R^2 = 0.95$). But if taxa are families then $w^{-1} = 2.00 \times 10^5$ and $t_1 = 70$ in the same units ($R^2 = 0.96$) (these values have been found by A.V. Markov and A.V. Korotayev, 2009).

For species there are no reliable data. However, observing the trend in parameter values in the series of families–genera–species, we can roughly assess for species $w^{-1} \sim 10^6$ taxa × million years and the singularity moment t_1 is disposed somewhere in the neighborhood of our time plus/minus several thousands of years, *because the depletion of species composition of the Earth's biota under anthropogenic impact has become just during the last several thousands of years*. As thousands of years are not appreciable on the scales of tens of millions of years, we can adopt $t_1 \approx 0$.

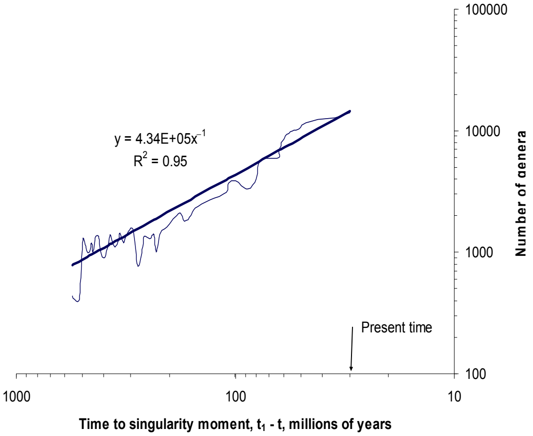

Fig. 8. Hyperbolic growth of biodiversity (total number of genera of the continental and marine biota) during the Phanerozoic (data source: A. V. Markov and A. V. Korotayev, 2008). Singularity is achieved at the moment t_1 = 30 millions of years.

The difference in singularity moments for the embedded taxa can be commented as follows. Considering the genera–family relation, we can notice that at the moment when the number of genera becomes infinite, the number of families remains finite. It means that at least one of the families becomes dominant tending to infinity. Similarly for the species–genera relation: at the moment of species singularity one of the genera becomes dominant also tending to infinity. It is clear that on the planet of a finite size the number of taxa cannot be infinite, but merely becomes large enough. It has not been clear yet whether this situation is possible from the biological viewpoint. At the same time, there is a suspicion that singularity must be achieved simultaneously for taxa of various levels, and the obtained discrepancy in singularity moments can be caused, for example, by high uncertainty in the original data.

Summarizing this section, we note the main conclusion: *there are two informational factors (macroparameters) that are subjected to the natural selection, these are: memory size* m *and knowledge production rate* w. *They equalize in the community providing the growth of the total memory size of civilization* R *and the total knowledge production rate* $\dot{q}$ *according to a hyperbolic law.*

6. TRANSITIONS WITH CHANGE OF DOMINANT MEMORY TYPE

The hyperbolic growth of biodiversity had been lasting until a taxon appeared in the biosphere that could develop its neuronal memory (mainly due to developing social relations – see: E. Herrmann et al., 2009), became to actively use it for producing and storing knowledge, and, due to that, occupied monopolistic positions in the biosphere (of course, we mean humans).

The transition from the domination of genetic memory to that of neuronal memory in one of the taxa led to a qualitative change of the evolutionary process: to the beginning of hyperbolic growth of dominant taxon abundance and the cessation of hyperbolic growth of biodiversity (the latter is because *the dominant taxon monopolizes and destroys the biosphere*).

At present, we observe one more transition that is associated with the development of external memory. This type of memory has undergone several qualitative changes. It has been used in incipient forms since early stages of anthropogenesis (e.g. instruments of labor as examples for copying) and became to develop appreciably since the appearance of written language, especially since the beginning of book printing era. By the present century the amount of only printed material is estimated circa 200 petabytes = 2×10^{17} bytes = 1.6×10^{18} bits (How much information, 2003). The fastest growth of external memory occurred only in the last time. It began since the creation of computers and went on with improvement of their facilities (memory size and speed). By the beginning of XXI century the total external memory reached the level of neuronal memory of humanity and then surpassed it (Fig. 3). The development of this memory type will be resulted in consequences similar to those that were in the prior transition, namely, to the appearance of a dominant taxon no longer in biota but in the human world community. Apparently, it will be a pool of countries in which knowledge produces most intensively. However, this results not in growth of population in these countries (because knowledge growth essentially raises the living standard and dramatically increases its cost causing a reduction of birth rate), but in the elevation of its informational and economic power. In this process, the external memory size R increases exponentially with knowledge: $R \sim e^q$ (this is a consequence of the logarithmic compression of information in producing knowledge), and the knowledge production rate grows proportionally to memory size: $\dot{q} = wR \sim e^q$, where w is the knowledge production rate per unit external memory size. Hence it appears that memory size obeys the equation $\dot{R} = wR^2$ yielding a hyperbolic time-dependence $R = w^{-1}(t_1 - t)^{-1}$, where $t_1 = (wR_0)^{-1}$ is the singularity moment, R_0 is the initial size of external memory (at $t = 0$).

To estimate the parameters, we take the year 2002 as initial, since for it there are data for the knowledge production rate $v = \dot{R}$. From the relationships $v = wR_0^2$ and $t_1 = (wR_0)^{-1}$, we find $w = v / R_0^2$ and $t_1 = R_0 / v$. According to the above estimates, we have for the external memory with prevailing magnetic carriers: $v \sim 10^{20}$ bits per year and $R_0 \sim 10^{21}$ bits (see subsection 3.3). These values give $w^{-1} \sim 10^{22}$ bits × years and $t_1 \sim 10^1$ years. Thus, the singularity moment in the development of external memory on magnetic carriers can be reached already during several decades. The type of carrier (magnetic) should be specified because, first, this type is basic now and, second, the appearance of a more improved carrier on an essentially different base (optics, graphene, or something other) will result in a significant increase in the information processing rate.

The calculated values of parameters are represented in Table 1 for various memory types. Emphasize that values of w are average for taxa of a corresponding level. For separate taxa this parameter will be scattered relative to the mean value. Note that the specific rates of knowledge production by the biota (per family) and by the humanity (per capita) coincide; however, a human (and a family in biota) produces knowledge twice faster than a genus and fivefold faster than a species (pay attention that Table 1 represents reciprocal values: w^{-1}).

The above analysis shows that *the transition to a new memory type gives rise to a new civilization with a faster development rate. This civilization holds dominant positions till the next transition. With every new transition the time since one of them till the next becomes nearly* *three orders of magnitude shorter than the previous one. Indeed, the duration of biological evolution on the basis of genetic memory is measured by billions of years; the duration of anthropogenesis on the basis of neuronal memory, by millions of years; and the duration of informational epoch on the basis of external memory, by thousands of years* (counting since the appearance of written language, though the domination of external memory has been reached quite recently).

By analogy with thermodynamics, biosystems with various dominant memory types can be regarded as phases, and the process of changing the dominant memory, as a phase transition. A thermodynamic phase consisting of particles is characterized in particular by chemical potential (defining as phase potential per particle) and a biological phase consisting of taxa, by memory size per taxon that can be named *biopotential*. The above-analyzed transitions in biosystems are not completed with establishing equilibrium between phases, since the development of the newly emerged phase goes on, its memory size grows, and biodiversity (the number of taxa) increases.

Parameters of hyperbolic growth for various memory types

Table 1

Memory type	**Reciprocal specific knowledge production rate w^{-1}**	**Singularity moment t_1**	**References**
Genetic memory in biota; taxa = families	2.00×10^{11} family × year	70 Myears forward since present time	Markov and Korotayev, 2009
Same; taxa = genera	4.34×10^{11} genus × year	30 Myears forward since present time	Ibid.
Same; taxa = species	$\sim 10^{12}$ species × year	Present time	Present work
Neuronal memory of humanity	2.00×10^{11} capita × year	Year 2027; exponent = –0.99	Foerster et al., 1960
	2.15×10^{11} capita × year	Year 2027; exponent = –1	Markov and Korotayev, 2009
External memory on magnetic carriers	$\sim 10^{22}$ bit × year	$\sim 10^{1}$ years forward since present time	Present work

In this sense the transitions considered are nonequilibrium phase transitions. A definite homeostasis (a kind of quasi-equilibrium) is possible when easily available resources have already been exhausted (due to the finiteness of biosphere), but possible only for a short while, until intrinsic changes in the system caused by accumulation of knowledge, development of new resources, and ripening of a new structure as a basis for a new memory type, eventually reveal themselves. And later on, a new memory type appears and a new phase transition occurs.

7. ADVANCE OF THE NEW CIVILIZATION

The rise of a new civilization in the depths of the old one is accompanied with competition for resources. If there is even a small advantage of the new civilization, it can reach dominant positions in due course. Suppose that the new civilization has a slightly larger memory or knowledge production rate and consider how this civilization rises. The autonomous development of each civilization proceeds in a hyperbolic regime. From the informational viewpoint, the interaction of both rival civilizations consists in that they try to impede knowledge production rate of each other.

Let $\dot{q}_1$ and $\dot{q}_2$ be the knowledge production rates in civilizations (or, in other words, the information flows circulating inside them). The second civilization influences the first one by the flow $\dot{q}_2$, and the first civilization tries to decrease this influence by means of its own flow $\dot{q}_1$. To completely get rid of negative influence of the rival, the first civilization must have its own flow much greater than the second one, so the external pressure on the first one becomes negligible at $\dot{q}_1 \to \infty$. Otherwise, if its own flow is small $\dot{q}_1 \to 0$, the pressure from the rival is completely determined by its flow $\dot{q}_2$. These limiting cases can be interpolated by the expression $\dot{q}_2/(1+\gamma_1\dot{q}_1)$ (multiplied by a constant coefficient) that describes the pressure of the second civilization on the first one. Thus, the competitive struggle on the field of information is described with the following equations:

$$\ddot{q}_1 = \dot{q}_1^2 - \beta_1\dot{q}_2/(1+\gamma_1\dot{q}_1), \quad \ddot{q}_2 = \dot{q}_2^2 - \beta_2\dot{q}_1/(1+\gamma_2\dot{q}_2),$$

where: $\beta_1, \beta_2 \geq 0$ are influence coefficients (describing intensities of external pressure), and $\gamma_1, \gamma_2 \geq 0$ are counteraction coefficients (intensities of counteraction against external pressure). The quantities q_i have been normalized in such a way that coefficients at $\dot{q}_1^2$ and $\dot{q}_2^2$ were equal to unity.

Let us consider the simplest case, when the external pressure does not meet with a rebuff on its action: $\gamma_1, \gamma_2 = 0$. Then the equations take the form:

$$\ddot{q}_1 = \dot{q}_1^2 - \beta_1\dot{q}_2, \quad \ddot{q}_2 = \dot{q}_2^2 - \beta_2\dot{q}_1.$$

Introducing the knowledge production rate $v = \dot{q}$, we rewrite these equations in the form:

$$\dot{v}_1 = v_1^2 - \beta_1 v_2, \quad \dot{v}_2 = v_2^2 - \beta_2 v_1.$$

At $v_1 = v_2 = 0$ we have an unstable equilibrium because any, even small informational disturbance (e.g. by receiving some information from the world) leads to a hyperbolic growth of civilizations. At $\beta_1 = \beta_2 = 1$ the solution is $v_1 = v_2 = 1$, but it is structurally unstable, because a small change in the parameters β_i results in the violation of equilibrium. In the general case, the equations cannot be solved analytically; therefore we have found a numerical solution at initial conditions $v_1(0) = v_{10}$, $v_2(0) = v_{20}$ that determine knowledge production rates in civilizations at the beginning of the process.

The computation results are depicted on Fig. 9. The top chart demonstrates the development of civilization under equal influence coefficients $\beta_1 = \beta_2$ but at slightly different initial flows v_{10} and v_{20} (the difference is only 10^{-4}). However, this difference appears to be sufficient to predetermine the fate of the less successful civilization (with less initial knowledge production rate). At a certain moment of time ($t = 1.11$ in relative units) it does not stand up to the competition and rapidly decays, though till this moment both civilizations developed practically in equal measure. The civilization with a slightly higher initial knowledge production rate continues to grow not responding to the loss of the rival.

The bottom chart shows the development of civilizations under equal initial rates $v_{10} = v_{20}$ but at slightly different influence coefficients. The civilization that acts more intensively on its rival survives and continues developing further, and the other civilization decays that happen at the moment $t = 1.09$.

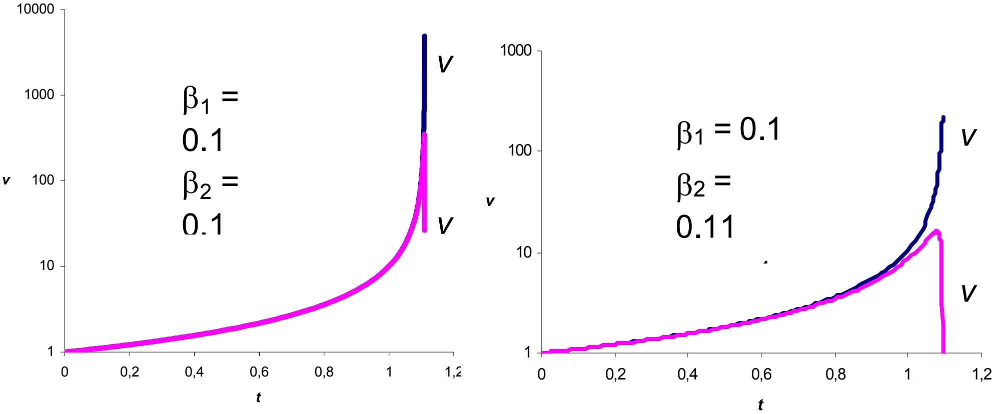

Fig. 9. Knowledge production rate versus time in the system of two rival civilizations: (a) under equal influence coefficients $\beta_1 = \beta_2$ and slightly different initial rates; and (b) under equal initial rates $v_{10} = v_{20}$ and slightly different influence coefficients.

Thus, a microscopic advantage of one of the rival civilizations is sufficient to win competition. This is only a question of time.

In connection with the collapse that overtook the less successful civilization it is appropriate to refer to the conclusion of May (2005) and D. J. Fisk and J. Kerhervé (2006) that a large dynamic system with a complex set of interactions between elements does not necessarily maintain dynamic stability as it grows in size, moreover increased complexity might be the cause of the collapse of civilization that is in accordance with the qualitative argument of J. A. Tainter (1995). Long-term social sustainability depends on understanding and controlling complexity (J. A. Tainter, 2006) or, in other words, on the amount of knowledge stored.

The analysis carried out can be illustrated by mutual relations of humanity and global biota. The advantages of humanity in the knowledge production rate have resulted eventually in the suppression of biota that opens ways to the monopolistic exploitation of natural resources accompanied with environmental pollution, destruction of biota, and disturbances in biotic mechanisms of climate control. Till the present time a part of disturbed terrestrial ecosystems reaches 60 % (World Resources Institute, 1988). In these conditions natural ecosystems are no longer able to restore themselves. So it is quite probable that the uncontrollable human impact on biota can result in a progressive deterioration of living conditions and a reduction in human population size. Different scenarios of this process have been considered earlier (B. M. Dolgonosov and V. I. Naidenov, 2006; B.M. Dolgonosov, 2009, 2010b) on the basis of the model developed there.

8. CONCLUSIONS

We have analyzed the connection between the dominant memory (genetic, neuronal, or external) and the type of civilization, supposing that a key trait of civilization is the production of knowledge needed for survival in the complex world. The analysis carried out demonstrated transitions between different types of civilization, which can be interpreted as nonequilibrium phase transitions. These transitions are developed in the following succession.

At the beginning of the formation of biota a reliable way of encoding and storing information on the basis of nucleotides appears. This way along with the natural selection allows finding and maintaining valuable codes. This induces growth of memory size that is necessary for accumulating vital information. The total memory size of biota grows according to a hyperbolic law, and the same law takes place for the growth of biodiversity (meaning the number of taxa) because taxa, as memory carriers, contribute to the total memory of biota. Further, as noted by A.V. Markov and A.V. Korotayev (2009), taxa gradually occupy ecological niches. However, because of the finiteness of the planet, easily accessible niches are eventually exhausted, so further appearance of new taxa becomes more and more energetically expensive. As a result, the growth of biodiversity slows down and deviates from the hyperbolic law that can be regarded as a transition growth regime toward the complete cessation of growth. According to the cited work, this new growth regime was observed at the end of the Cenozoic era, approximately from the beginning of anthropogenesis.

Long before the beginning of the transition, yet on the stage of hyperbolic growth, the biota finds a new way of encoding information on the basis of nerve cells. This originates a parallel development of a new memory – neuronal, which is used initially for regulation of physiological functions, and then more and more for processing sensory information. Further, a taxon appears with more developed neuronal memory both by its volume and by processing information rate (especially due to the development of cortex and, on this basis, “cultural memory”). In this process (we mean the anthropogenesis) the neuronal memory becomes eventually dominant. Its total size grows by a hyperbolic law just like the population of the taxon. The hyperbolic growth of population goes on until the finiteness of planetary resources becomes noticeable. Then, population growth rate starts reducing that is observed since the second half of XX century with further tendency to the cessation of growth or even to depopulation.

Meanwhile, the expanding humanity develops a new memory type on the basis of external carriers – cultural artifacts, physical specimens, images, texts, and finally computer carriers. In due course the external memory surpasses neuronal one by size and becomes dominant. Its total size also grows by a hyperbolic law. The external memory is replenished by almost all humans (though unique valuable information among all of the replenished is small), but the store of knowledge is contributed mainly by developed countries. These are the countries that form a taxon (a pool of countries) in the world human community, which develops most rapidly and therefore represents the dominant taxon. Knowledge production demands large investments in science, education, high technologies, and altogether in economics and culture. Far from all countries have such means, and it is unlikely that the developed countries took on themselves a burden to finance these spheres of activities in alien countries especially with inefficient, corrupt regimes. It would seem that the Internet lifts these restrictions making it possible to use information in any place on the planet independently of that where the information has been produced. However, this fact too little helps in the development of their own infrastructure of knowledge production, economics, and culture. The current globalization does not predetermine equal levels of the development of countries participating in this process. Always there will be scientific and technological leaders and will be countries with less or even very low developmental level, which play an auxiliary role of suppliers, for example, of raw materials, consumer goods, and labor force. Since the growth of knowledge and economic power obeys the hyperbolic law, there will be no keeping up with leaders.

Thus, the appearance and development of every new type of memory leads to radical changes in the structure of old civilization and to the emergence from its depths of a new civilization developing more rapidly.

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