Self-Regulation as a Global Evolutionary Mega-Trend

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The article introduces and describes the notion of 'self-regulation' which allows combining the processes of different nature and complexity into a single trend associated with self-preservation, operation, transformation and increasing complexity of systems in the course of interaction with changing environment. Meanwhile, the study of self-regulation can become an integrative methodological approach uniting various areas of knowledge, such as Cybernetics, Synergetics and Evolutionary Studies. The author traces the manifestations of self-regulation within Big History and its important role in evolution, especially in mega-evolution and in evolutionary transitions to new levels of complexity. One can observe the signs of self-regulation even at the early stages of Big History, for example, during the formation of the first stars. We can also see different alternatives and mechanisms of self-regulation in chemical evolution at the level of systems lacking operating controls. The origin of life became the most important qualitative transition of self-regulation and its complication in the evolutionary context. The systems passed from self-organization and self-adjustment to simple and later complex control. The developed nervous system, especially the brain, became the first self-controllable system. Later the biosocial branch of self-control (including human society) emerged in which self-control is even more vividly manifested in some respects.

However, within evolution the self-regulation is inherent not only to chemical, biological, and social systems. In the present paper we show that in the coming decades the self-regulating systems will emerge and spread in a new form, i.e. in the form of human-created self-regulating technologies. It will result from the new production revolution which we call the Cybernetic one. Its first phase has already begun, and the most mature phase will start between the 2020s and 2030s. This revolution will lead to critical transformations in economy and society and will significantly change the world as well as human modus vivendi.

Keywords: *self-regulation, self-control, Big History, mega-evolution, evolution, the Cybernetic Revolution, Synergetics, self-organization, Cybernetics.*

The Universal history (or, as it is often called, Big History [Christian and McNeill 2011]) is based on a number of universal principles and evolutionary laws (Grinin 2013b, 2014). At different times and in different environments they show up in different ways and with different intensity. At the same time, in spite of the fact that 'the class of systems is terribly wide' (Ashby 1969), there are certain basic similarities within formation and behavior of systems at all evolutionary levels, in other words there exist certain patterns (Grinin and Korotayev 2014).

The present article is devoted to one of such understudied patterns, namely, the self-regulation in systems whose role is undervalued in evolutionary studies. We believe that self-regulation is one of the universal and basic characteristics of complex systems and plays an important role in evolutionary processes. Self-regulation is observed in various natural realms – from an atom and molecule (Makino *et al.* 1992) to populations of animals (Wynne-Edwards 1965), from a cell (Miyake *et al.* 2011) to societies and the World-System (Grinin and Korotayev 2009, 2014; Bandura 1999; Cummings 1978; Grinin *et al.* 2012; Pearce 1987). Meanwhile, in the course of evolution the significance of self-regulation increases together with the system complexity.

Concepts of Self-Regulation

We define self-regulation as a system's ability to preserve stability and basic parameters within changing environment. The definition shows that we consider self-regulation as a broad concept which incorporates various aspects of maintaining stable state of a system.

There are scarce researches of self-regulation; yet, some of its forms are studied in Cybernetics and Synergetics. Meanwhile, self-regulation is characteristic of both complex and simple systems.

In some cases self-regulation is connected with self-organization. Without exaggeration self-organization is one of the key concepts of Cybernetics and Synergetics introduced by the founders of these sciences William Ashby (1962) and Hermann Haken (1985). According to Haken, self-organization is adjustment of the open system due to coordinated interaction of the variety of constituent elements. And though the concept of self-organization is frequently used in a broad meaning, for example, when speaking about self-organization in biosphere or society (Moiseev 2001), nevertheless, self-organization is first of all the process of spontaneous emergence of order and organization from disorder (Mikhailov *et al.* 2012) and consequently, it is characteristic of systems only under certain conditions.

One more way for the relatively simple systems to support their state is self-adjustment. In self-adjusting systems the changes occur in the values of these or those parameters whereas self-organization implies changes in the structure of a system in general (Glushkov 1986). Self-adjustment usually changes a small number of parameters. It can be also considered as a simple form of self-regulation.

In more complex systems self-regulation occurs due to the action of other mechanisms as well as due to the ability to 'accumulate experience', that is to 'store' or 'memorize' information. As a result systems can more effectively maintain their state under changing conditions. Self-regulation in such systems is based on the 'choice' made by the system. According to Ashby, one of the pioneers in the studies of complex systems, 'to the extent that each determined system acts to maintain a balanced state, it makes choice' (Ashby 1959). In other words, to achieve an equilibrium state, the system objectively makes choice by rejecting some states while preserving only the ones which it transforms into. Consequently such 'memorization' of information and variability of alternatives sometimes can also create essentially new situations bringing the emergence of more successful and efficient models thus opening a way for the evolution.

In Cybernetics the complex systems are studied from the point of view of control[1] starting from highly organized biological organisms (not the full range but just those with the central nervous system), as well as technological and social systems (Beer 1963; Glushkov 1986; Rozanova 2009). Basing on the concept of self-regulation (which in complex systems also incorporates control), we try to extend some ideas and principles of Cybernetics to larger scales, including inanimate nature.

In the developed complex systems we especially emphasize the importance of control in self-regulation. As a result in some such systems the self-regulation passes to a higher level of self-control; therefore, we call them self-controlled systems (below we will speak about them in more detail).

Self-Regulation in Terms of Cybernetics and Evolution

As we have already mentioned, self-regulation is the systems' ability to preserve stability and basic parameters under changing conditions. This ability is already observed during the transition of systems from chaos to a stable (self-organized) state. Self-regulation generally develops due to the maintained stable state under changing conditions via creation of various mechanisms or protectors smoothening or minimizing negative impact of the environment. While interacting with the environment, especially in the search for a response to its dramatic changes, a system can pass to a new stable state with the increase (or decrease) of its developmental level. As we see self-regulation is anyway a part of evolutionary process.

The evolutionary role of self-regulation can be properly considered within the cybernetic approach to the interaction between systems and information. Each acting subject can absorb information from the external environment and apply it to select a proper behavioral pattern via transforming and distributing information among subsystems or various elements of the system. One should consider that the most part of information is distorted by interference and 'noise' on the way to the object and inside it and is lost in the struggle with entropy which is information-distorting chaos. For any systems entropy is an inevitable background, condition and at the same time, a byproduct of their operation.

Self-regulating systems, especially those having the control components, are able to reduce the system entropy via the distribution of functions and efficient information processing. According to Wiener, 'there are local and temporary islands of decreasing entropy in a world in which the entropy as a whole tends to increase'. The mechanism of their emergence consists in natural selection of stable forms; here physics directly drifts into cybernetics (Wiener 1983).

While struggling with entropy, systems try to isolate from the environment since the more open the system is, the more probable is its slide to chaos. However, this contradicts the second law of thermodynamics. In the 1870s Ludwig Boltzmann formulated the rule according to which the total entropy of an isolated system always increases over time, or remains constant in ideal cases (Landau and Lifshits 1976). Then, where do the 'local and temporary islands of the decreasing entropy' which Wiener spoke about originate from?

One of the explanations is that complex systems can regulate the extent of their closeness via self-regulation, avoiding the increasing entropy and steeping of the whole system into chaos. Thus, Boltzmann actually meant that success of systems in the struggle with

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[1] Cybernetics is a science about common patterns of receiving, storage, transfer and transformation of information in complex regulating systems.

entropy is only temporal and eventually any system can hardly exist eternally and is likely to be destroyed. However, this period of successful fight of systems with entropy can be rather long (*e.g.*, stars live for billions of years) and it anyway constitutes the life time of systems.

The second reason explaining the contradiction is that while reducing entropy locally, the systems increase the amount of entropy on a global scale. For example, plants convert light energy into chemical energy thus, reducing the 'local' level of entropy. This, in turn, affects the connections between systems and breaks the common order. Thus, the converted by plants solar energy is the source of energy for every living thing including people who by their actions create instability and destroy the existing links between living organisms, thereby increasing entropy on the whole planet.

Generally speaking, the decreasing entropy underlies the evolution of systems and is a good example of manifestation of the law of unity and conflict of opposites. Thus, in order to escape chaos, the systems tend to become isolated which, in its turn, allows their transformation and increasing complication. At the same time the developing and complicating systems are quite scarce in number comparison to stagnating systems, and according to Eric Chaisson they are only 'the islands of the growing complexity' (Chaisson 2012).

Another important aspect of Cybernetics which allows considering the role of self-regulation in evolution in detail is control. As we have already told, it is the most important element of self-regulation of complex systems and one of the universal mechanisms for maintaining stability. Control is very important for understanding the evolutionary mechanisms since according to Darwin an unintended consequence of evolution is the selection of the most advantageous forms.

One can speak about control in system in case when behavior of cybernetic systems changes under controlled actions, *i.e.* in a systemic manner. Control just as self-regulation in general is focused on the maintenance of constant values of certain variables. Control is characteristic of complex and super-complex systems in which adaptation to changing environment and also 'perception' of laws of such changes become urgent.

Within cybernetic approach control can be schematically presented via two components: the object of control and controlling system. The controlling system interacts with the object of control via direct links often through numerous intermediaries presented by the peripheral components. Besides, the controlling system incorporates the system of receiving signals from environment. The latter, being far from always stable or 'friendly', can act as a source of various interference and distortions. In this case the controlling system is in charge for the filtration of interference.

One of the simplest types of control is the operation mode with a preset program (programmed control). For example, the traffic lights work in this mode. The simple control systems (automatic regulation systems) already can be responsible for constant maintenance of a variable. For example, the modern air-conditioning systems have ambient air temperature sensors and controlling systems which compare the ambient temperature with the preset variables and launch actions to maintain the necessary temperature. More complex systems can already maintain some fixed functional dependence between the variety of spontaneously changing parameters and a set of regulated parameters (*e.g.*, the system which accompanies with searchlight a maneuvering plane).

There also exist optimal control systems. They are capable of supporting the amplitude of values of a certain function from two types of parameters: environmental conditions (which change irrespectively of the system) and regulating parameters whose values can change under the influence of system's control signals. Thus, for example, the ambient temperature sensor can possess an optimal control if it additionally monitors humidity. If environment changes, an optimal control system can maintain constant values of regulated parameters. The relatively simple systems achieve similar stability by selecting corresponding parameters for the projected system while more complex systems can employ self-adjustment. This is an important manifestation of the law of evolutionary complication when some independently working mechanisms providing a system's interaction with environment (like self-adjustment) combine as parts of sophisticated regulation (control) in more complicated systems.

In more complex systems some control variables which are not fixed in advance can be changed by the system itself in the course of its functioning. For this purpose the system has a special unit which monitors the character of transition processes in the system when the latter loses its balance. When turning out in an instable state, the system changes the links setting until it reaches a stable state. Such systems are often called ultrastable.

If the number of changing parameters becomes too large, then it can take the control system too much time to randomly search for stable modes. In this case more complex systems impose various restrictions on the random search, for example, divide the communication parameters into groups and select only within one group. In Cybernetics such systems are usually called multistable. One can observe a great variety of ultra- and multistable systems in wildlife. One of the examples of multistable systems can be temperature regulation in humans and other warm-blooded animals.

The method of ‘block assemblage’ which is rather common in evolution is also present in multi- and ultrastable systems. The ‘block assemblage’ means that when responding to changing situation a system employs a block of parameters which previously proved to be efficient under similar conditions. It is especially evident in the genome where everything is recorded at the level of code; meanwhile, the records are divided into logical units. At present, programming develops along a similar pathway. The object-oriented programming forces out the procedural programming due to its mobility, variability, and, above all – cost-saving support and development.

In complex systems control often separates into a subsystem or even a number of subsystems. Thus, animal nerve cells which at first were spread over most of the body merged into a single nervous system – a control system of the organism.

Being able to maintain the balance under the influence of various unstable conditions, some ultra- and multistable systems acquire the ability of learning and independent decision-making, and even of modifying their mechanisms of interaction with environment, as well as to control themselves. We denote such systems as self-controllable systems.

In Cybernetics the concept of self-control is applied (Beer 1963) only for living and social systems and not for technical and other artificial systems (biotechnical, programmed, *etc.*). Meanwhile, we extend the concept of self-controllable systems to such kind of highly complicated and ‘smart’ systems which increases opportunities of using the cybernetic principles for characteristics of many already existing and projected technologies.

However, self-controlling is a particular case of self-regulation and its most developed form. Further we will describe how self-regulation has been manifested in the evolution of the Universe, delineate its role in evolution, and the way certain self-regulating systems developed self-controlling features and what we can expect here.

Self-Regulation in Stars

The complicated issues of maintaining an energy balance of stars have already been studied rather well (Hopkins *et al.* 2011; Nishi and Tashiro 2000; Thomas *et al.* 2010). Self-regulation supports stable stars at different stages of their evolution (Grinin 2014).

Thus, self-regulation in its initial form of self-organization promotes the formation of stars through condensation and compression of gas clouds under the influence of gravitation forces.

It is a rather long-lasting process since it unfolds over about 50 million years (Surkova 2005: 50). During this period, there is a tremendous rise in temperature at the core of a protostar, the temperature may grow up to 8–10 million Kelvin, and, as a result, thermonuclear reactions become possible. The protostar turns into a young star. However, an external observer will only be able to see it in a few hundred thousand (or even a few million) years when the cocoon of gas and dust surrounding the protostar dissipates.

One may also note that the emergence of stars and galaxies should have a certain trigger that generates turbulence and heterogeneity. Those triggers and catalyzers are the inherent components of evolutionary mechanisms that may be traced in many phenomena: in chemical and geological processes, fast formation of species within biological evolution, as well as state formation in social evolution (for more details see Grinin 2011). The supernova shock wave, the expanding envelopes of the forming stars as well as the collision of a molecular cloud with spiral arms of a galaxy and other events can become such a trigger for the star formation in a cloud (Surkova 2005: 50).

During the longest phase of life (the so-called main sequence) the star can preserve its initial size and shape. This phase is associated with the hydrogen consumption and maintenance of balance at the expense of energy production and consumption.

The evolution to the red giant phase is connected with hydrogen burn-up at the center. The gas pressure (that maintained the star balance when necessary fuel was available) decreases and the stellar core compresses. This leads to a new increase in temperature. A star starts to burn heavier elements. At this stage the self-regulation shows up in the fact that after exhaustion of certain types of 'fuel' (in particular, hydrogen) stars can switch to its other types. The stellar composition significantly changes. In general, the star inflates and expands a few hundred times, and it transforms into a red giant; and at this stage it is able to keep its new shape for hundreds of millions of years.

The red giant or supergiant undergoes certain transformations at the next stage. There are three possible most typical outcomes depending on stellar mass. Stars with the masses smaller than 1.2–1.4/3 solar masses evolve from red giants into the so-called 'white dwarfs', when the star sheds its outer envelope to form a planetary nebula with an extremely contracted core (down to the size of the Earth). A white dwarf is very hot when it is formed; yet, afterwards the star cools and transforms into a 'black dwarf', that is, it becomes a cold dead cosmic body. For stars with initial mass of more than 1.2–1.4/3, but less than 2.4–3/7–10 solar masses, their slow and gradual aging results in an 'infarct' (*i.e.* a collapse). After the depletion of hydrogen and the decrease of the internal gas pressure the stars get extremely compressed just in a few seconds. Almost simultaneously the external layers of the star are blown away with a huge speed as a result of shock wave. This supernova shines brighter than millions of ordinary stars, but for a very short period of time. This explosion expels the stellar material into interstellar medium and thus, there occurs the formation of considerable quantities of heavy (heavier than iron) elements that afterwards concentrate in various celestial bodies. The remaining core contracts to become a neutron star which is five billion times smaller than the Sun but hundreds of thousands of times brighter since the temperature on its surface is 1000–1500 times higher than on the Sun (Lipunov 2008: 133).

If stellar mass exceeds the limit of 3/7–10 solar masses, after hydrogen is burnt out it will start collapsing and explode (though sometimes it may collapse without an explosion), but the force of compression will be unlimited since the gravity becomes enormous because of the huge mass and absence of internal forces that can prevent the collapse. The action of the gravitational force which is balanced by nothing leads to the situation when the stellar diameter becomes infinitesimally small. According to theoretical calculations, the star is transformed into a black hole whose gravity fields are strong for light to escape.

Death of stars shows well that possibilities of systems to self-regulation and maintenance of balance with the environment are finite (and in this context we have already considered Boltzmann's idea). But first of all the death of systems provides opportunities of regeneration, and secondly, the development of larger systems may also transform the smaller order systems (see below). Pierre Teilhard de Chardin (1987) fairly considered that life is stronger than organisms. One should add here that evolution is stronger than individual systems. The laws of renewal and cycling of matters (when the new appears from the decayed old) are very important evolutionary laws in which self-regulation plays an important role.

Another version of primary star formation, described by Igor Shklovsky (1984), which at present, however, seems already outdated, shows that during the early period along with massive stars many small stars also formed which became the subdwarfs practically without heavy elements. Massive stars, having a short 'lifespan', exploded, and the frequency of these explosions used to be dozen times larger than today. It enriched the interstellar environment by heavy elements and ended rather quickly, several hundred million years before the earliest history of the Universe (it often happens in evolution that the number of deaths of the first generation and transitional forms is much larger than of the subsequent and more stable ones). This example shows that stars which are capable of self-regulation themselves form a system which is also capable of self-regulation. In this case self-regulation plays the role of an evolutionary driving force since it promotes the selection of the most stable forms. This is the simplest and most widespread self-regulation in the Universe whose rules still work at different scales. For example, modern galaxies also form the self-regulating systems which are described by various models (Hopkins *et al*. 2011; Kim *et al.* 2011; Trujillo-Gomez *et al.* 2014). According to one of the viewpoints (which is not generally accepted, but nevertheless rather interestingly describes the opportunities provided by self-regulation), the galactic centers are a kind of a 'Moloch' milling stars into gas and dust as well as creating new generations of stars in place of them. Expelling them together with gas-and-dust matter into the intergalactic space, the galaxies thus 'rejuvenate' the Universe, promoting a continuous cycling of matter in it. Thus, the natural cycling of matter which rejuvenates and mixes the matter occurs at all levels – both spatial and evolutionary.

On the whole, it is important for the development of self-regulation and evolution that the external environment maintains stable parameters for a rather long period. The more stable the parameter is, the greater is its evolutionary role[2]. Thus, water, oxygen, and sunlight remain the major elements of evolution of life without essential changes for billions of years. In self-regulation of stars it is the gravity that has a similar importance. It plays a great role in cosmic evolution, allowing stars to be formed of gas-and-dust clouds uniting galaxies into assemblages, *etc.*

One may say that at the first stages of Big History the simple types of self-regulation prevailed. Today they also generally prevail in the Universe. Meanwhile, the self-preservation gradually increased due to more efficient mechanisms of self-regulation. Thus, the first stars containing a small amount of heavy elements and consisting largely of hydrogen and helium were bigger in size, less stable and had shorter lifetime than modern ones (for more details see Grinin 2013a). With accumulation of other chemical elements in the Universe the self-regulation among stars increased, and along with the emergence of the new generation of stars the lifetime of these systems was also increasing (*Ibid.*).

Self-Regulation in Chemical Revolution

Almost from the very beginning of the development of the Universe (when the temperature reached thousands of Kelvin) the emerging chemical evolution accompanies physical and astrophysical evolution.

Chemical evolution also proceeded within stars in the course of formation of heavier elements in them. Chemical reactions that resulted in the formation of new substances from different elements occurred generally in gas-and-dust clouds. At first hydrogen molecules prevailed quantitatively; however, molecules of water and other substances were formed as well. Chemical evolution also happened on planets (where it was combined with geological, more precisely planetary evolution), as well as on small celestial bodies (meteorites, asteroids, *etc.*). At the same time chemism in cold clouds was significantly different than on the planets with rather high temperatures due to volcanism, pressure and other geological processes.

Following Friedrich Engels (in his 'Dialectics of Nature') the representatives of dialectic materialism argued that the chemical form of matter organization is evolutionary superior than physical. However, unlike biological or social forms which since their emergence were marked as an essentially higher form of the organization of matter, the chemical form which appeared soon after physical remained evolutionarily insignificant for very long time. The same is true for the geological form which emerged on planets long ago, but which succeeded to develop only after it had created conditions suitable for the emergence of life. One can hardly agree that chemical evolution was of little significance within the general cosmic evolution; however at least prior to the Earth's formation the physical and chemical forms of matter organization should be considered as equivalent, passing from one into another (Dobrotin 1983). In many respects the chemical form may be considered as a 'preadaptation' for new evolutionary levels. Let us remind that in biology the term 'preadaptation' defines a situation when the achievements generally play an insignificant role (not taking the concrete organism into consideration) in the environment where they emerge. But a breakthrough at some point appears impossible without them. As a result at a certain evolutionary level the forms possessing such preadaptations gain huge advantages and become evolutionary superior or leading. They can trigger the formation of new taxa and filling of new ecological niches.

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[2] Though, on the other hand, sharp changes of earlier stable conditions often become the leading factor of evolution. The law of dialectics of the unity and struggle of opposites is shown in it.

The emergence of organic molecules even to a greater extent can be considered as a preadaptation. The formation of molecules, including organic substances (in particular in gas-and-dust clouds), already achieved a certain level of complexity. More than hundred molecules of organic substances (including 9–13 atomic structures) are found in outer space including even such substance as ethyl alcohol (Surdin and Lamzin 1992; Shklovsky 1984). This is the manifestation of multilinearity of evolution since the classical chemical reactions on our planet have their analogues in the Universe. As a result, the evolutionary multilinearity is further implemented in the synthesizing of the achievements of its different forms (chemical and geological) as it happened on the Earth and which gave a chance to move to the new evolutionary level.

The significant breakthrough in the development of chemical substances resulted from prebiotic evolution (*i.e.*, preceding the emergence of life) (Rauchfuss 2008). Chemical substances have a very high potential for self-organization since they can crystallize, passing from the disordered structure into an ordered one. At the same time the crystal surfaces can serve as a matrix for emerging macromolecules (Chernov 1990). Thus, the synthesis of proteins becomes possible in water solution containing one of clay minerals. The clay minerals in water solutions can pull and hold various charged organic molecules, and the metal ions can catalyze the reactions of macromolecules and embed in their structure.

As has been already mentioned, it is evolutionary important that the basic parameters remained constant for long periods of time. Within prebiotic evolutionary framework there are different views about what became such a basic parameter.

According to one of the approaches, the intensive prebiotic synthesis of organic molecules could proceed on the surface of minerals of iron sulfide (Saghatelian *et al*. 2001). The logic is that such geological conditions on the young Earth were widespread. For example, there could be the so-called 'black smokers', that is the supposed 'oases' for the emergence of life at the ocean floor with high pressure and temperature, without oxygen and with abundance of various compounds which could serve as a construction material for 'life bricks' or a catalyzer in the chain of chemical reactions (Lucien 1990).

Self-Regulation in Living Systems

As has been already mentioned, the self-regulating systems are very widespread in the living world. A cell, body, and an organism are examples of such systems.

Self-organizing chemical molecules became more complicated in the course of evolution of life. There emerge complex interconnections and new parameters, for example spatial structures, isomerization and homologization. Chemicals acquired the ability to arrange cycles, chains, to change links and form, to include catalyzers into their structure, *etc.* There appeared reactions with feedback[3].

However, in order to move to a new evolutionary level, the chemical substances needed some important elements of control including code information determining the order and features of reactions for reproduction and self-regulation.

According to the common version, the RNA became the first molecule of the kind. It is also argued that at first protein was a coding molecule, however, it apparently 'lost' due to weak variative abilities (Grigorovich 2004). The peculiarity of RNA is that it contains rather simple, but extremely variable nucleotide code and it also has a feedback through

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[3] Modern organic substances may have very complex behavior. *E.g.*, the chlorophyll molecule is complex to the extent that scientists cannot still reconstruct its functioning (Rau *et al.* 2001).

special enzymes and moreover, it is capable of self-reproduction, *i.e.* replication, which is a rather vigorously proceeding process. It should be noted that ancient RNAs were significantly shorter than the modern ones (Smith *et al*. 2014). There are some reasons to suppose that the shorter RNA is, the more active it is. This can be evidenced from Spiegelman's experiment (with the so-called Spiegelman's monster). During the experiment the extracted RNA together with special enzyme – RNA-replicase – was inserted into a solution of free nucleotides. In this environment the RNA started to replicate. After a while the RNA was taken and inserted into a new fresh solution. This process was repeated many times. Shorter RNA strands replicated faster. After 74 generations the original RNA of a virus with 4,500 nucleotide bases was reduced to 218. This short RNA, Spiegelman's monster, was able to replicate with an incredible speed. Later Manfred Sumper and Rudiger Luce showed that in the solution containing no RNA at all, but only nucleotides and enzyme, under certain conditions a self-replicated RNA can spontaneously emerge and can evolve into a form similar to Spiegelman's monster (Sumper and Luce 1975).

Self-reproduction was an enormous step forward in self-regulation of substances and to self-control. The RNA molecule became the basis for the emergence of DNA, the latter being the main information storage (the simplest living organisms still contain RNA). DNA is not just an algorithm of all possible actions. It is hard to imagine how long DNA strand should be to contain all algorithms accumulated for billions of years. Instead, it contains only basic algorithms. This reflects the rule of modularity, or evolutionary 'block assemblage' which we have already spoken about.[4] It gave an opportunity to accumulate 'life experience' and reproduce it from generation to generation. Due to the lack of regulating system the first organisms searched for a response to changing conditions by testing combinations. The code system made it possible to refuse it since it became sufficient to refer to available experience. Systems absolutely different in their nature – from living to social and technological ones – started to use this method of control. The block assemblage principle of formation of new subsystems, systems and groups is characteristic of the most different systems. Moreover, the transfer of experience may proceed not only within a system but also among several systems. The biological and social systems can borrow certain 'inventions' from each other. For example, the prokaryotes have a widespread ability of 'natural transformation'. In other words they can acquire DNA from the external environment and embed it into their own genome which leads to an immediate transformation of phenotype.

A peculiar manifestation of the rule of 'block' assemblage is complex borrowings of whole gene systems, a particular case here are the symbioses widely spread in fauna. For example, the land plants form symbioses with nitrogen-fixing bacteria and mycorrhizal fungi, and with insect pollinators. All animals have symbioses with specialized microorganisms, for example, those helping to digest food (Grinin *et al.* 2012).

Symbiosis is not a new invention. One may reasonably suppose that this form of cooperation was peculiar for pre-life and initial life forms. Besides, there could even emerge a complex symbiosis when elements merge into a new system, as it probably happened to chemical elements which united into so-called coaservative drops – the clots similar to water solutions of gelatin. Due to their chemical properties they can merge and form water-repellent hollow spheres concentrating various chemical elements. According to wide-

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[4] It is interesting that among the first to introduce the block-assemblage principle of living organisms (and also of the natural selection) was Empedocles who believed that living beings were collecting in a random manner from ready parts (heads, legs, *etc.*) and the successful combinations survived and the others – failed.

spread hypotheses of the origin of life on Earth, the coacervates became the ancestor of a living cell. The author of this theory is the Soviet biochemist, academician Alexander Oparin. Following this scientist and irrespective of him the English scientist John Haldane came to similar conclusions. Oparin believed that the transition from chemical evolution to the biological one required the emergence of individual phase-independent systems capable of interaction with the environment (Oparin 1941). Thus, the creation of isolated self-regulating system helped the chemical substances to form biological systems (Serebrovskaya 1971; Troshin 1956).[5]

The first living organisms were obviously rather unstable. But this was a frequent evolutionary phenomenon among the transitional forms which have not developed the properties of a completed system yet but due to their potential they have very considerable capacities for transformations. This also gives additional impetus to evolution, but at the same time it can also be connected with the diminishing potential to self-regulation, since the ability to evolve and to maintain stability are generally opposite trends though in some cases their synthesis occurs, and then an evolutionary breakthrough can happen. For this reason the transitional forms often do not leave traces (see also Teilhard de Chardin 1987). Thus, the first stars 'lived' less than modern ones. During revolutions the forms of legislative and administrative organizations as well as constitutions often change in a kaleidoscopic manner due to a search for the most appropriate and steady forms, *i.e.* the forms with a high level of self-regulation.

On the whole one may say that at the dawn of evolution of life the emergence of macromolecules, such as RNA, DNA, proteins, enzymes, *etc.* in the course of chemical evolution, led to huge variations and required the creation of control systems. The more complicated the system became, the more complicated control it needed. Yet, to overcome entropy, the systems tried to create mechanisms to isolate themselves from direct and non-systemic contacts with environment by forming protective (insulating) covers, so that it could be possible to regulate contacts of internal parts of the system with the environment. The first coacervates formed in that way and later – the cells. The cell became the main self-regulating living system due to which organisms were formed by the pattern of 'block assemblage' in the process of evolution.

Life gradually developed. The regulating system of the life forms became complicated and began to isolate itself into a separate nervous system. The peripheral system and analyzers for providing feedback also started to develop. The development of central neural system, especially brain, became the starting point of formation of self-controllable systems. Organisms acquired the ability to make complex solutions, analyze behavior and environment, study and share accumulated experience. The developmental level achieved by the human brain without exaggeration can be considered the most complex self-controlled systems ever known.

Life also materialized self-controlled systems in the form of biosocial systems. The groups of individuals of the most different lines of evolution managed to create communities which generally functioned as a complex and uniform self-controlled system. Beehive, ant hill, and human state have many similar features in self-regulation. They have a control center and peripheral systems and can make independent decisions, respond flex-

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[5] In the present article the author does not aim at analyzing the disadvantages of Oparin's theory. This theory attracts attention as a possible illustration of manifestations of self-regulation. Meanwhile, the theories of the extraterrestrial origin of life are rather popular nowadays. But they can be also considered in terms of self-regulation.

ibly to the environment changes and are capable of learning. Thus, the multilinearity is well manifested in evolution. Self-controlling as an efficient form of self-organization emerged at the most different levels of evolution: from an organism's subsystem (in the form of nervous system) to supra-organism level. Self-regulation also shows up in non-biological systems (see below).

Self-Regulation in Society and Technological Revolutions

Self-regulation in History

As it has already been mentioned, the human society is a complex self-regulating system. One can trace the changing size and complexity of social forms from simple (*e.g.*, communal, local, affined or other small groups) to intermediate (bigmen settlements, small tribes, simple chiefdoms or their analogues), and then to complex societies (large hierarchical chiefdoms, urban communities and policies, confederations of tribes or communities, *etc.*), also including the early states (Grinin 2011; Grinin and Korotayev 2009). One can also notice how the early states became more complex and stable over millennia as they passed to the evolutionary stage of the developed states that are centralized and more stable societies with a close correlation between social and political systems. Later one can observe how in the course of the transition to industrial production the developed states began to transform into the mature ones, consolidating not the poorly united nations consisting of regional groups with common cultural and language features, but the cultural and literate nations united by common ideology and modern communications. Finally, we can see how in the twentieth century the mature class states riven by internal social conflicts began to transform into social states whose major task was to support the indigent and unprotected strata of population (on the evolution of statehood see Grinin 2010).

The transition to every new complexity level was associated with increasing complexity of regulation and levels of control. Thus, for example, a simple chiefdom has three levels of control: chief, heads of certain settlements or quarters, and households. And even the most primitive state has four or five levels of control while a modern state has more than seven or eight levels. Moreover, certain subsystems of a state, its certain departments, corporations, *etc.* enhance the ability to self-control, as well as to complex cooperation within a larger system. All this can become the subject for a further research.

However, we would like to focus on another aspect of development of self-regulation. We assume that scientific and technological progress reached the point when self-regulation in technologies has transformed into the most developed form of self-control. It will especially show up in the next decades and will bring the humankind to a new stage of evolution when a human will be able to influence the biological nature via technologies. Here we should make a survey of the history of the most significant technological transformations.

Production Revolutions and Increasing Complexity of Technical Systems. According to our conception (Grinin 2006, 2007; Grinin A. L. and Grinin L. E. 2013; Grinin L. E. and Grinin A. L. 2015), among all diverse technological and production changes which occurred in history three revolutions had the most far-reaching and universal consequences for society. We define them as production revolutions. They are the following:

1. The Agrarian, or Agricultural Revolution. Its outcome was the transition to systemic food production and complex social labor division based on it. This revolution was also associated with the emergence of new source of energy (animal power) and materials.

2. The Industrial Revolution concentrated the main production in industry to be performed by machines and mechanisms. The significance of this revolution consists not only in the manual labor substitution by machine production, but also in the substitution of biological energy for water and steam power which provides opportunities of labor-saving.

3. The Cybernetic Revolution at its initial phase brought the emergence of powerful information technologies, new materials and sources of energy as well as spread of automation; and at the final stage there occurred a transition to a wide use of self-regulating systems.

The Cybernetic Revolution

The Cybernetic Revolution is the greatest technological breakthrough from the industrial principle of production to production and services based on the implementation of self-regulating systems. On the whole, it will become the revolution of the regulating systems (see Grinin 2006, 2013c; Grinin A. L. and Grinin L. E. 2015a, 2015b).

This revolution is called Cybernetic because its main point consists in the formation and wide spread of self-regulating systems (for more details see Grinin L. E. and Grinin A. L. 2015). We rely our analysis of self-regulating systems on the ideas of Cybernetics as a science about regulation of various complex controllable systems (biological, social and technical) (see Wiener 1983; Beer 1963, 1994; Ashby 1966; Foerster and Zopf 1962; Umpleby and Dent 1999; Tesler 2004; Glushkov 1986; Rozanova 2009; Mogilevsky 1999; Plotinsky 2001; Easton 1997).

The Cybernetic Revolution began in the 1950s. In this period advanced technologies underwent automation and became more effective. There occurred great changes in energy production which also increased the efficiency of technologies. Significant breakthroughs occurred in the spheres of automation, energy production, synthetic materials production, space technologies, exploration of space and sea, agriculture, and especially in the development of electronic control facilities, communication and information. On the whole one should note that this period became the stage of formation of modern and future technologies. The majority of modern devices were created and tested in the middle of the last century, and even much earlier. This can serve as another example of the preadaptation in evolution of systems.

In the mid-1990s the intermediate (modernization) phase of the Cybernetic Revolution started which, according to our assumptions, will last till the 2030s. It is characterized by significant improvements and spread of innovations that were made at the initial phase, in particular by a wide use of easy-to-use computers, communication means and systems, network information technologies, as well as the formation of the service macrosector with information and financial services becoming of great significance. At the same time the innovations necessary to start the final phase of the Cybernetic Revolution are prepared.

The final phase of the Cybernetic Revolution will begin between the 2030s and 2040s and will last till the 2060s and 2070s. There will be a transition to widespread use of self-controllable systems at this phase. We define as self-controllable those systems that can autonomously control their operation with minimal human intervention or totally without it.

Self-Control in the Cybernetic Revolution

As we have already mentioned, self-control is the most developed form of self-regulation.

Self-controllable systems differ from other self-regulating systems in a number of parameters:

1. Self-controllable systems are more efficient which is partially connected with the distribution of functions. The isolated control centers are more productive for the analysis of information and provide more opportunities for the formation of feedback.

2. Self-controllable systems are capable of complicated learning and decision-making. The learning ability is one of the key features of the animals' developed nervous system which played an important role in evolution. In the Cybernetic Revolution the ability of machines to make decisions independently and to learn makes them potentially attractive to investments and large-scale production, and can also become one of the solutions of the problem of reduction of labor during the coming demographic crisis.

3. Self-controllable systems possess a great variability. The more complex structure and behavioral patterns of systems provide a great variability and increase the ability to development.

Just as in the course of their complication and evolution the simple self-regulating elements were transformed into complex self-control ones (*e.g.*, the animalcular elementary neurons into the central nervous system), so technologies pass from mechanical to automated, from automated to self-regulating and then to self-controllable. Certainly it does not mean that each technology has to follow this developmental path. Already today along with the automated and self-regulating systems there exist self-controllable technologies, especially in space industry. The life-supporting systems (such as medical ventilation apparatus or artificial hearts) can regulate a number of parameters, choose the most suitable mode of operation, detect critical situations, and, in fact, make vitally important decisions. There are also special programs that determine the value of stocks and other securities, react to the change of their prices, buy and sell them, carry out thousands of operations every day and fix a profit. And these are only a few examples among already existing variety of self-controllable systems.

One of the indicators that technologies ‘aspire’ to be self-controllable is the distribution of ‘smart’ technologies and things which flexibly react to environment. The pillow which ‘remembers’ a shape of human head can be a simple, but a bright example. Another example is the transition glasses with glasses changing color depending on lighting. The range of complexity of ‘smart’ systems is rather wide. Some systems of the kind can surely be called self-controllable, for example, ‘a smart house’ whose system will control all important parameters in the house and adapt them to owners' tastes. As an example of self-controllable system one may call self-driving cars which have already developed nowadays.

The artificial intelligence will also be a self-controllable system about which a lot of works have been written in the last decades (see, *e.g.*, Poole *et al.* 1998; Hutter 2005; Luger 2005; Russell and Norvig 2009; Neapolitan and Jiang 2012; Keller and von der Gracht 2014; Hengstler *et al*. 2016).

However, one should emphasize that the concept of self-regulation and self-control is wider than the concept of ‘artificial intelligence’. Within the Cybernetic Revolution most of the technologies are not related to artificial intelligence (*e.g.*, the genetic engineering or biotechnological systems). Even within the IT technologies autonomous management does not develop only in the direction of artificial intelligence which is a more peculiar case. Technologies will generally ‘aspire’ to increase their efficiency and at the same time many technologies will become ‘smart’ or ‘intellectual’ (see Russell and Norvig 2009). However, even ‘intelligent’ technologies will hardly become artificial intelligence; the same way, for example, the living organisms (and even anthropoid apes) far from always aspire evolving into a human with an advanced brain.

If not all technologies evolve towards artificial intelligence, so in what direction will the Cybernetic Revolution and self-regulating systems develop then? In our opinion, between the 2020s and 2030s, there will take place a breakthrough in medical technologies which will incorporate a number of other leading directions. In general they will make a complex of MANBRIC-technologies: medico-additive-nano-bio-robotics-info-cognitive technologies.[6]

The leading role of medicine in the Cybernetic Revolution is first of all connected with global aging, increasing lifetime and the need of socialization and employment of elderly people and disabled people under the conditions of labor reducing. A wide variety of technologies will be directed to health support.

Already today in the medical sphere some major innovations ripen which will reach their maturity in two or three decades (some of them even earlier) (Grinin L. E. and Grinin A. L. 2015). Modern medicine is closely related to biotechnologies, pharmaceuticals, gene technologies, industrial chemistry, and some other branches, *etc.* At the same time health care costs are constantly increasing. Thus, from 1995 to 2010 the expenses on medicine have grown twice – from 454 dollars a year to 950 dollars per person along with a notable population growth (World Bank 2016).

During the Cybernetic Revolution various technologies of constant health control of organism including those based on biotechnologies can get a special widespread. Nanotechnologies will lead to continuous miniaturization of technical devices that allow reducing the sizes of biochips in order to implant them directly into organism. It will give an opportunity to have a constant control over important parameters of organism and to report critical deviations.

Bionics, transplantation, neurointerfaces and similar directions are especially important in connection with rapid aging of population. Along with other technologies they will help resolving the problem of labor shortage due to the increasing working capacity of the elder age groups.

Robots will become another leading self-controllable technology capable of solving the problem of labor shortage. In the next decades in the developed countries robots will perform either mostly or completely some professional duties (presumably telemarketing services, accounting, auditing, retailing, the real estate deals, in economy and aviation, *etc.*) (Frey *et al.* 2013).

In general during the final phase of the Cybernetic Revolution there will appear a lot of self-controllable systems connected with biology and bionics, physiology and medicine, agriculture and environment, nano- and biotechnologies. The number and complexity of such systems, as well as the autonomy of their operation will dramatically increase. Besides, they will allow a considerable energy and resource saving. Human life will become more and more organized by such self-regulating systems (*e.g.*, via monitoring of health, regime, regulation or health recommendation, control over patient's condition, prevention of illegal actions, *etc.*).

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[6] We believe that it will be a broader system of innovative technologies, than it is usually considered; in particular, broader than the NBIC convergence.

However, one should emphasize that during the Cybernetic Revolution, according to our forecasts, the increasing opportunity to change and modify the biology of the human body will become especially important.

In other words, we are at the threshold of a post-human revolution. Perhaps, it will be not as radical as transhumanists think, but anyway it implies an essential prolongation of life, a replacement of an increasing number of organs and elements of biological organism by abiological materials, most various implanted self-controllable systems into organism for rehabilitation or improvement of human's functionality.

Certainly, it will take not less than two or three decades from the first steps in this direction (in the 2030s and 2040s) to the universal broad application. Thus, self-controllable systems will bring evolution to a new level; it is impossible yet to make predictions about all the consequences of this process.

Conclusion

In our opinion, the descriptions of the systems' ability to preserve stability in changing environment lack some universalizing concepts which can refer both to simple and complex systems including living, social, technological, *etc.* Therefore, we introduce an important for a number of reasons notion of 'self-regulation' which widely describes the capacity of systems for self-preservation in the situation of changing environment.

First, the concept of self-regulation allows combining into a single trend (and under a single term) the processes of different complexity related to self-preservation, changes, functioning and complication of systems in the changing environment. Moreover, the studying of self-regulation can become a basis for creation of integrated methodology combining such important cross-disciplinary areas of knowledge as Cybernetics, Synergetics, and Evolutionary Studies. So far as known, the synthesis of these important research fields was hardly performed in this respect.

Secondly, our research shows that self-regulation plays a significant role in evolution, especially in mega-evolution and in the evolutionary transitions to new complexity levels, since in the course of adaptation or 'adjustment' of systems to sharply changing external conditions there may happen some important qualitative changes that further can broadly or even universally extend.

Self-regulation is revealed at the early phases of Big History, in fact, with the emergence of the first systems (*e.g.*, the first stars). We show that to a certain extent self-organization can be considered as one of the initial forms of self-regulation and at the same time as the most widespread in the Universe. The capacity for self-preservation gradually increased due to emergence of more effective mechanisms of self-regulation. With the accumulation of other chemical elements in the Universe the ability of stars to self-regulation increased, and with the emergence of the new generation of stars the lifetime of these systems also increased.

In chemical evolution different alternatives and mechanisms of self-regulation at the level of systems without control can also be seen. This stage of evolution resulted in a great chemical diversity and became the main threshold to a new quality in self-regulation which we can observe with the emergence of life. The emergence of self-replicated molecules which allowed accumulating experience and reproduce it from generation to generation became an extremely important stage. It provided 'block structure' character of evolution and considerably accelerated it. The biological systems clearly demonstrate the complicating self-regulation within evolution. From self-organization and self-adjustment, the systems passed to simple and later to complex control. There was developed an ability to receive and analyze information: the analyzers, peripheral systems, controlling system and regulating system became complicated. The central nervous system became a key link in control and was enormously developed in the course of evolution. The developed nervous system, especially brain, became the first self-controllable system.

Some kinds of organisms, including a human, developed complex biosocial self-controllable systems.

As a result of emergence of states and civilizations the society became a true self-controllable system capable of conscious changes and redevelopment. Society also developed as a result of technological revolutions. The technologies originated by the human mind were constantly complicating. Modern technological revolution which will last for about half a century and which we call the Cybernetic will become an epoch of development and distribution of self-controllable technologies. The final and the most mature phase of the Cybernetic Revolution will begin in the 2030s.

On the whole the study of self-regulation expands our knowledge about the interaction between systems and external environment which is also important for understanding of the evolution of systems. The development of self-regulation in the course of evolution involved an important transition from uncontrollable to controllable systems and from controllable to self-controllable systems. These transitions are important for understanding of evolutionary processes since they reveal some mechanisms of quality transition to complex systems. The study of self-regulation and self-control within the new (Cybernetic) production revolution allows understanding of the key trends as well as making some predictions about its development.

In this regard we believe that the study of self-regulation and self-control is significant and promising, and we hope that our research makes a certain contribution here.

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