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The Cybernetic Revolution and Singularity*

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Abstract

This article considers a long-term dynamics of technological progress, providing one of the options for measuring its rate throughout the entire historical process. We are based on the theory of technological (or production) revolutions and the theory of production principles, which allow to measure the speed of technological progress as well as to make some predictions. It has been found that the general dynamics of accelerating technological growth over the past 40,000 years can be described with amazing accuracy ($R^2 = 0.99$) by simple hyperbolic equation: $y_t = C/t_0 - t$, where y_t is the technological growth rate, measured as a number of technological phase transitions per unit of time, while t_0 and C are constants, whereas t_0 can be interpreted as a 'technological singularity' point. Although the rate of technological progress since 40,000 BP in general has been increasing, following a hyperbolic acceleration pattern, however, according to the theory of production principles and historical facts, the acceleration of technological progress has noticeable fluctuations. These fluctuations can be explained by the fact that technological development proceeds within the framework of super-long cycles. It is shown that within these cycles,

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the phases of accumulation of basic breakthrough innovations are replaced by the phases of rapidly growing improvements and their wide distribution. The point of singularity and the possibility of radical changing of the previous technological progress pattern are also discussed. According to our calculations, based on the selection of the most important phase transition periods in technological evolution, the singularity date is expected to happen in the early 22nd century.

There is an idea that technological progress has been slowing down from the 1970s. However, as already mentioned, there are strong fluctuations in the acceleration of technological progress. According to the theory of production principles, after the 2030s we expect a new powerful acceleration of technological development followed by its slowdown in the late 21st and early 22nd centuries. Our idea is that global ageing will be one of the major factors of this technological acceleration and then, by the end of this century and the beginning of the next century, on the contrary, it will be a brake on scientific and technological progress. The socio-economic mechanisms for such acceleration and deceleration are considered in detail.

Keywords: *technological progress, long-term dynamics, breakthrough innovations, accelerating technological growth, the rate of technological progress, global ageing.*

1. Introduction

On Increasing Speed of Historical Process

In the today's world people deal daily with numerous achievements of scientific and technological progress. People are becoming more and more dependent on them, spending a considerable amount of time keeping pace with progress. In general, the entire human history, especially during the last few centuries may be regarded (albeit, with significant qualifications) as a history of achievements of science and technology, especially information technologies (Kurzweil 2005; Galor and Tsiddon 1997; Kremer 1993; Carree 2003; Phillips 2011; Kayal 1999; Grinin L. and Grinin A. 2015c, 2016; Grinin L., Grinin A., and Korotayev 2017a). Thus, technological growth is one of the most important factors of the society's transformations and development. Therefore, it is extremely important to identify some patterns in the history of technological development, and try to anticipate the forthcoming transformations in technology and society. Unfortunately, there are a few well-grounded researches which could describe technological development in a systematic and consistent way and provide scientific explanation of why and how the technological revolutions occur.

The issue of the technological growth rate has been discussed for many years (*e.g.,* in journal *Technological Forecasting and Social Change*). Researchers have presented interesting (but often contradictory) scenarios and had a lot of debates, among which it appears necessary to single out the Huebner – Modis debate on the possible declining trend for worldwide innovation (Huebner 2005; Modis 2005), as well as discussions dealing with Kurzweil's singularity (Ayres 2006; Modis 2006; Magee and Devezas 2011; Linstone 2014). There are also (albeit in insufficient quantities) works that provide consistent forecasts of technological development based on the identified developmental trends (Modis 1999; Martino 2003; Farmer and Lafond 2015).

One can observe a strong interconnection between different factors of a society. The transformations in some of them can cause changes in others. Even though no factor can be considered as absolutely dominant, some factors of society are more significant with respect to their influence on others. Accordingly, the changes taking place within them are more likely to affect other interconnected factors.[1] We believe the technological factor is one of the most important and influential due to the following reasons:

1. Significant changes in the production basis lead to more surpluses and throughout most of human history to a rapid population growth which in its turn strongly influences production growth as well as rate of innovations (Kremer 1993; Korotayev 2005, 2006b, 2007a, 2008, 2012; Grinin 2011a, 2012b, 2016). These processes led to the changes in all other spheres of life (Grinin 2006b, 2007a, 2009, 2012a, 2017; Grinin and Grinin 2015a, 2015c, 2016; Korotayev 2006a, 2007b, 2009, 2013; Korotayev, Zinkina, *et al*. 2011; Korotayev, Zinkina, and Andreev 2016). Meanwhile, the transition to new social relations, new religious forms, *etc.* is not as directly related to economic and demographic changes as technological transformations.

2. Though a significant surplus can be explained by some other factors (natural abundance, successful trade, war, *etc.*), exceptional conditions cannot be reproduced, whereas new productive forces can be reproduced and diffused, and thus, they appear in many societies.

3. Production technologies are implemented by the whole society (and most importantly, by working social strata).

It is important to consider that the higher the rate of technological change, the more noticeable the impact of technological progress on social change and cultural evolution. The historical process tended to gear up with the accelera-

[1] One should note that we do not mean continuous and regular influence but rather a qualitative breakthrough. If after a breakthrough within a more fundamental sphere other spheres do not catch up with it, the development within the former slows down (for more details see Grinin 2006a, 2007a; Grinin and Grinin 2015a, 2015c, 2016; Grinin and Korotayev 2009).

tion of technological growth, whereas neither individual, nor public consciousness could keep up with it. This arouses a quite reasonable alarm about our future. In this regard, any research that allows anticipating changes in the rate of technological innovation is important. In the article, based on the studies of all previous technological development, we will try to predict possible fluctuations in the pace of technological development in the forthcoming decades. As we have noted before, though it is extremely difficult to predict directions and main features of technological development, we believe, however, it is possible. Firstly, we think it is possible to forecast the development of important processes by understanding their past and present rhythms and trends in order to predict future development, and secondly, by using some theories which can describe relatively recurrent patterns at specific time intervals (Grinin L., Grinin A., and Korotayev 2017a).

Objectives of the Study

This article aims (1) to suggest a theory explaining in some aspects the mechanisms and cycles of large-scale technological changes (revolutions) with a brief presentation of technological evolution throughout the historical process in accordance with the theory; (2) to propose the concept and methodology for measuring the speed of technological evolution, starting from the deep antiquity and up to the first decades of the 22nd century; (3) to forecast when and why the speed of technological progress will change in the near future. The structure of the article corresponds to these tasks.

The Structure of the Article

The article consists of an introduction, four main parts (Sections 2–5) and conclusion. In Section 2, we briefly present the basic ideas of the theory of production principles with a short description of technological changes during the entire historical process, as well as some predictions about the new wave of technological changes (the final phase of the Cybernetic revolution) before the end of this century. Thus, our research covers a very wide time span between the Upper Paleolithic or Human Revolution (Mellars and Stringer 1989) and the forthcoming 'posthuman' revolution the consequences of which are still unclear and which will obviously start a new era.

Sections 3–4 are devoted to the mathematical interpretation of technological progress in accordance with the proposed model and the methods described below. In the Section 3 we present a mathematical interpretation of the chronology described in the Section 2. According to the theory of production principles, within every production principle, each of its six phases plays functionally the same role, while the ratio between the duration of phases, within the framework of each cycle, remains approximately the same. Based on this finding, we have empirically determined certain correlations between the duration of the phases recurring within each of the three previous production principles. This makes it possible to forecast the future phases of the current production principle (Scientific-Cybernetic).

Section 4 presents calculations of the rate of technological progress and determination of the date when its slowdown will begin. The last part (Section 5) is devoted to the problem of the relationship between global ageing and technological progress, since we consider global ageing as one of the most important (and fundamentally new in history) factors, that can accelerate and then slow down the scientific and technological progress. The conclusion is devoted to the question of the possible impact of global ageing on changing the current consumption model.

Materials and Methods

To solve the abovementioned tasks, we use, firstly, the theory of production principles, which has been developing for almost 30 years. It allows understanding the logic of technological development within the historical process and the suggested periodization. The theory has been described in detail earlier (Grinin 2006a, 2006b, 2007a, 2007b, 2012a, 2012b, 2013; Grinin L. and Grinin A. 2013a, 2013b, 2014, 2015a, 2015b, 2015c, 2016; Grinin and Korotayev 2015a; Grinin L., Grinin A., and Korotayev 2017a). Secondly, using rather simple mathematical methods we have found the general pattern of the acceleration of technological growth rate (*i.e.*, operationalized as the frequency of technological phase transitions per unit of time). In particular, for this purpose, we apply the methodology proposed by Alexander Panov and also one based on the other works (in particular of Modis [2002, 2005, 2012]). We use well-known mathematical equations that allow comparing our results with the results of researchers who measured the rate of general evolution on Earth. We also pay some attention to the question of the singularity in the acceleration patterns, since there are grounds to expect that its detection could help to identify important inflection points in the processes under study.

The issue of Big Global History singularity has been discussed quite actively for more than a decade (see, *e.g.*, Panov 2004, 2005a, 2005b, 2006, 2008, 2009, 2011, 2017; Kurzweil 2005; Ayres 2006; Modis 2006; Muehlhauser and Salamon 2012; Magee and Devezas 2011; Eden *et al.* 2012; Shanahan 2015; Callaghan 2017; Korotayev 2018; Nazaretyan 2015, 2016, 2017, 2018). This subject became especially popular after the Raymond Kurzweil's (Google's director of engineering) book *The Singularity Is Near* (2005). We think that the 'Singularity Hypothesis' may be quite useful for the theory of the historical process as we will show below. It can also help in analyzing the causes of deceleration and acceleration of scientific-technological progress. Singularity can indicate an exhaustion of the accelerating process and allows ascertaining the specific mechanisms of its deceleration, as well as fluctuations of its speed. This is all the more important because technological development forecasts are often based on empirical or phenomenological generalization, for example, Moore's law (Kurzweil 2005; Farmer and Lafond 2015), which has no sufficient theoretical explanation and apparently ceases to operate for various reasons (see, *e.g.*, Kish 2002).[2]

We seek to identify actual mechanisms and relationships to explain the reasons for possible slowdown in the speed of the technological process in the future. We associate significant changes in technological development with global ageing in the future (as one of the most important results of technological progress), but, as we will see, the impact of ageing on the rate of technological progress is non-linear and creates different effects at different phases.

It is worth noting that the impact of global ageing on the speed and direction of scientific-technological progress is understudied (Galor and Weil 2000; Prettner 2013; Tsirel 2008; de Grey and Rae 2007). The ideas of F. Fukuyama (2002) have not lost their significance in this respect either (*e.g.,* his ideas about possible future ageism [Fukuyama 2002]; for our analysis of the risks connected with global ageing see Goldstone *et al.* 2015; Grinin L. and Grinin A. 2015c, 2015d, 2017; Grinin L. and Grinin A. 2016; Grinin and Korotayev 2010, 2015b, 2015c, 2016a, 2016b; Grinin L., Grinin A., and Korotayev 2017a). The problem, however, is connected not only with the consequences of global ageing but with the identification of mechanisms of complex interaction between ageing and technological progress. These consequences can appear in a new light if we understand the abovementioned connections with their positive and negative feedbacks. So, the problem is very important. There has never been time in human history, when the elderly made up such a high proportion of the population as it is now, but in the future this proportion will be even higher, leading to various and unpredictable consequences (Harper 2006; Powell and Khan 2013; Goldstone 2015; Goldstone, Grinin, and Korotayev 2015; Coleman and Rowthorn 2015; Park and Shin 2015; Haas 2015; Grinin and Korotayev 2016a, 2016b, 2016c; Zimmer 2016; Grinin, Grinin, and Korotayev 2017a). The course of further social evolution will largely depend on the response to this challenge. It is also important to take into account that the impact of global ageing will

[2] There are different views on the growth function of technological progress: an exponent (Kurzweil 2010), a super exponent (Nagy *et al.* 2011), a logistic curve (Ayres 2006), Multiple S Curves (Sood and Tellis 2005). Also, different types of technologies develop with different rates and functions (see, *e.g.,* Koh and Magee 2006).

become increasingly tangible, but at different stages it will have different (positive or negative) effects on scientific and technological progress.

In this paper we combine various methods: historical, comparative, evolutionary, logical, theoretical modeling and mathematical.

The novelty of our research lies in the attempt to provide a concise framework for a qualitative model in which the rate of change in the population age structure correlates with the development of future technologies.

We obtain a nontrivial result, according to which in the coming decades the process of global ageing can accelerate and change the direction of technological progress, and then in the late 21st and early 22nd centuries an ageing society can slow down scientific and technological progress.

One can assume that the current consumption pattern may also change under the influence of the global ageing process. And this, in turn, will have an extremely serious impact on the entire production structure and scientific and technological progress (we will discuss this issue further).

The present article is a continuation of our research regarding characteristics and patterns of the technological progress in the framework of historical process as well as the correlation between global ageing and technological development (Grinin L., Grinin A., and Korotayev 2017).

2. The Development of Historical Process in the Light of the Theory of Production Principles

2.1. Production Principles and Production Revolutions

There has been made a large number of technological breakthroughs. As we have already argued (*Ibid.*), among significant technological breakthroughs in history the most important are **the three technological or production revolutions**: 1) the Agrarian Revolution (the Neolithic Revolution); 2) the Industrial Revolution; and 3) the Cybernetic Revolution. From our point of view, each revolution initiates a new stage of development of the world productive forces as well as transition to a new stage of technological evolution. The point is that each production revolution means the transition to a fundamentally new production system; the beginning of each production revolution marks the borders between corresponding production principles. Thus, according to the theory of production principles, technological development trend within historical process can be subdivided into four major stages, or *production principles.*

We single out four *production principles*:

1. Hunter-Gatherer;

2. Craft-Agrarian;

3. Trade-Industrial;

4. Scientific-Cybernetic.

Thus, production principles are connected with production revolutions. The starting point of such revolutions can be regarded as a convenient and natural point to establish the chronology of changing patterns.

1. Agrarian Revolution (12,000–10,000–5,500–3,000 BP). Its result was the transition to a systematic production of food, using new type of energy (power of domestic animals), and, on this base, the transition to a complex social division of labor. This revolution was also connected with the use of new power sources (animal power) and new materials.

2. Industrial Revolution (the last third of the 15^{th} – the first third of the 19^{th} centuries), which resulted in the main production being concentrated in industry and production being carried out by means of machines. Not only was manual labor replaced by machines, but also biological energy was replaced by water and steam energy.

3. Cybernetic Revolution (from 1950 to the 2060/2070s) which has already led to the emergence of powerful information technologies, and in the future will stimulate transition to the wide use of self-regulating systems in different spheres of activity, which will be able to function without human intervention. The Cybernetic Revolution is not over yet. We believe, it will provide significant steps towards improving human health, the quality of our life and the ability to influence and control human body (for more details see below; see also Grinin L., Grinin A., and Korotayev 2017a; Grinin L. and Grinin A. 2015a, 2015c, 2016).

Phases of Production Principles

Every production revolution can be regarded as an integral part of the production principle. Production revolution is the first 'half' of the production principle, whereas during the second half the development of mature technologies, based on production principle, occurs.[3] The cycle of production principle can be represented in six phases. Our mathematical analysis is based on this six-phase pattern. The cycle looks as follows:

1. The first phase – *starting* – is the beginning of production revolution. A new production principle emerges in one or a few places, although in rather undeveloped incomplete forms.

[3] The cycle of each production revolution looks as follows: *the initial innovative phase* (emergence of a new revolutionizing production sector) – *the modernization phase* (diffusion, synthesis and improvement of new technologies) – *the final innovative phase* (when new technologies acquire their mature characteristics). For more information about a cycle of production revolutions and their structural interconnection with production principles see Grinin L., Grinin A., and Korotayev 2017a (as well as our abovementioned works).

2. The second phase is *the stage of primary modernization*. It is associated with a wider diffusion of new production forms as well as with strengthening and vigorous expansion of a new production principle.

3. The third phase is *the stage of completion of production revolution.* The production principle acquires advanced characteristics.

4. The fourth phase is *the stage of maturity and expansion of a production principle*. It relates to diffusion of new technologies into most regions and spheres of production. The production principle acquires its mature forms and this leads to important changes in socioeconomic sphere.

5. The fifth phase is *the stage of absolute dominance of a production principle in the world*. It leads to an intensification of production and the full realization of the potential of the principle.

6. The fifth phase is *the stage of non-system phenomena, or a preparatory phase for the transition to a new production principle.* New inventions and improvements of technologies lead to the emergence of non-system elements which prepare the formation of a new production principle. Under favorable conditions these elements form a new system. The current cycle is thus completed but in some societies the transition to a new production principle starts and the cycle will repeat but at a new level.

Based on this six-phase cycle of the production principle, we perform our calculations of technological progress rate, where the transition from one stage to the next is considered as a phase transition. The following paragraphs in this section are devoted to the description of the history of technological changes in the macroperiod under consideration.

2.2. The Hunter-Gatherer Production Principle

Its *first* phase (40,000–30,000 BP)[4] may be related to the 'Upper Paleolithic' Revolution (for more details see Mellars and Stringer 1989; Marks 1993; Bar-Yosef 2002; Shea 2007, 2013; Markov 2012; Mellars *et al.* 2007; Powell *et al.* 2009) and the formation of social productive forces (no matter how primitive they were at that time [see Grinin, Korotayev, and Markov 2012; Grinin L. and Grinin A. 2015c]). Already for this period more than a hundred types of tools are known (Boriskovsky 1980: 180; see also Tattersall 2008: 150–158; 2012: 166–173; Jochim 2011b; about the technological and instrumental 'legacy 'of the anthropogenesis see d'Errico and Backwell 2005; Anati 2008; Markov 2011a, 2011b; Jochim 2011a).

[4] Henceforth, all dates for the Hunter-Gatherer and Craft-Agrarian production principles and some others are rather approximate, rounded up or down for the calculation's goal (for variations of the dates see Grinin L. and Grinin A. 2015c, 2016).

The *second* phase (approximately and rather conditionally, from 30,000 to 22,000 BP) led to the final elimination of which could be called *residue contradiction of anthropogenesis*: between biological and social regulators of human activities (for more details see Grinin and Korotayev 2009; Grinin L. and Grinin A. 2015c). This phase is associated with a wide diffusion of humans, their settlement in new places, including the peopling of Siberia (Doluhanov 1979: 108) and, possibly, the first wave of the peopling of the New World (Zubov 1963: 50; Sergeeva 1983; Korotayev, Berezkin *et al.* 2017). Yet, the dates are very scattered (Mochanov 1977: 254; Sergeeva 1983; Berezkin 2007a, 2007b, 2013).[5]

The third phase lasted from 22,000 till 17,000 BP. This was the period of the maximum spread of glaciers (referred to as the last glacial maximum).[6] And though this was not the first glaciation, this time humans had a sufficient level of productive forces and sociality so that some groups managed to survive and even flourish under those severe conditions. Considerable changes took place with respect to variety and number of tools (Chubarov 1991: 94; Jochim 2011b; Shea 2013). It was at this time that the types of stone tools were rapidly changing; for example, in France and other European regions (Grigoriev 1969: 213; Jochim 2011b), in the Levant (18,000 BP) microliths appeared (Doluhanov 1979: 93; Shea 2013). In many places during this and forthcoming stages the major evolutionary changes associated with the Epipaleolithic were increasing economic intensification and population growth (Shea 2013: 162).

During the subsequent fourth phase – *c.* 17,000–14,000 BP – the level of adaptation to the changing environment significantly increased (Jochim 2011b, 2011c). In some places that avoided glaciation, an intensive gathering developed (Hall 1986: 201; Harlan 1986: 200; Fainberg 1986: 185; Goring-Morris *et al*. 2009; Shea 2013). Proto-craft development was also observed during this period, including sewing and weaving, making clothing, and basketry (see Dyatchin 2001: 37).

The fifth phase – from 14,000 to 11,500 BP – that is the late (final) Paleolithic and the early Mesolithic in Europe may be related to the end of glaciation

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[5] The genetic data dates this period to 25–15 thousand years ago (Goebel *et al.* 2008). Still the settlement of Americas was a complicated and long-lasting process (Berezkin 2017; Korotayev, Berezkin *et al.* 2017).

[6] During the last glacial epoch, Würm III, the glacial maximum was observed about 20,000–17,000 BP when temperatures dropped by 5 degrees Celsius (Velichko 1989: 13–15). About the technology and archeological evidence see Jochim 2011b; Shea 2013. For designation of cultures which were not completely or partly affected by the end of the glacial age, as, *e.g.* for the Levant, North Africa and southwest Asia during the period after the Upper Paleolithic and before the Neolithic, between approximately 20,000 and 10,000 years BP archaeologists use the term 'Epipaleolithic', *i.e.* 'Final Paleolithic'. So it overlaps with the late Upper Paleolithic and Mesolithic in Europe (Shea 2013). In our periodization the Epipaleolithic connects with the third–sixth phases.

and climate warming (Yasamanov 1985: 202–204; Koronovskij and Yakushova 1991: 404–406; Shea 2013; Goring-Morris and Belfer-Cohen 2017). This warming together with the consequent change in the landscape decreased the number of large mammals. That is why the transition to individual hunting was observed and also new tools appeared (Markov 1979: 51; Childe 1948: 40; Fainberg 1986; Jochim 2011c; Shea 2013; for some later period see Simmons 2013). The technical means (bows, spear-throwers, traps, nets, harpoons, new types of axes, *etc.*) were developed to support the autonomous existence of smaller groups and even individual families (Markov 1979: 51; Prido 1979: 69; Avdusin 1989: 47). Fishing in rivers, lakes and sea was developed and acquired major importance (Matyushin 1972; Ritchie *et al.* 2016; Bergsvik and Ritchie 2018; Lozovskaya *et al.* 2018). There developed the following types of stone arrowheads: leaf-shaped, fluted, hollow-base, and winged arrowheads. The bone and wood arrowheads took an indented and later barbed and harpoon shape (Semyonov 1968: 323, 324).

The *sixth* phase (*c.* 11,500–10,000 BP) was also connected with ongoing climatic warming and environmental changes culminating in the transition to the Holocene (see, *e.g.*, Hotinskij 1989: 39, 43; Wymer 1982) and in archaeological terms in the transition to the Neolithic in connection with considerable progress in stone industries (Semyonov 1968; Monghite 1973; Avdusin 1989; Yanin 2006; Milisauskas 2011b). This period evidenced a large number of important innovations that, in general, paved the way to the new, Craft-Agrarian, production principle (see, *e.g.*, Mellaart 1975; Ammerman and Cavalli-Sforza 2014; Shea 2013). Of peculiar interest are the methods of harvesting, which could potentially prove a more progressive development of the craft-agrarian mode since such harvesting can be very productive (see, *e.g.*, Antonov 1982: 129; Shnirelman 1989: 295–296; 2012a; Lips 1956; Lamberg-Karlovsky and Sabloff 1979; see also Tanno *et al.* 2013; March 2013; Conte *et al.* 2018; Lozovskaya *et al.* 2018).

2.3. The Craft-Agrarian Production Principle

The first phase of the Craft-Agrarian production principle was at the same time the beginning of Agrarian (or, in traditional name, Neolithic) revolution. The beginning of the Agricultural Revolution often is dated within the interval from 12,000 to 9,000 BP (though in some cases the traces of the first cultivated plants or bones of domesticated animals are even older, *e.g.* 14,000–15,000 years ago). As one sees, we take some intermediate date interval for the initial innovative phase of the Agrarian Revolution / *first* phase of the Craft-Agrarian production principle, *i.e.* 10,000–7,300 BP. It is worth noting that the term Neolithic revolution can be connected only with this phase and the beginning of the next one of the Agrarian revolution. Whatever plants were cultivated, the independent invention of agriculture always took place in special natural environments (with respect to South-East Asia see, *e.g.*, Deopik 1977: 15). Correspondingly, the development of cereal production could only occur in certain natural and climate conditions (Gulyaev 1972: 50–51; Shnirelman 1989: 273; 2012a; Mellaart 1982: 128; Harris and Hillman 1989; Masson 1967: 12; Lamberg-Karlovsky and Sabloff 1979; Ammerman and Cavalli-Sforza 2014; Milisauskas 2011a, 2011b). The cultivation of cereal crops is supposed to have started somewhere in the Middle East: in the hills of Palestine (Mellaart 1975, 1982), in the Upper Euphrates area (Alexeev 1984: 418; Hall 1986: 202), or Egypt (Harlan 1986: 200). A fairly large set of plants was domesticated and cultivated. Thus, according to some data in southern and eastern China, 97 different plants were cultivated (Londo *et al*. 2006). This period ends with the formation of the West Asian agricultural region, and on the whole one can talk about the formation of the World System during this period (Korotayev 2005, 2007a, 2012, 2013; Korotayev, Malkov, and Khaltourina 2006a; Grinin and Korotayev 2009, 2012, 2013a, 2013b, 2014a, 2018), also including its first protocities (about protocities and first cities see Lamberg-Karlovsky and Sabloff 1979; Masson 1989; Schultz and Lavenda 1998: 214–215; Balter 2006; Korotayev 2006b; Korotayev and Grinin 2006, 2012, 2013).

The *second* phase can be conventionally dated to 7,300–5,000 BP (from the sixth to the mid-to-late 4th millennia BCE), that is up to the formation of a unified state in Egypt and the development of a relatively sophisticated irrigation economy in this country. It includes the formation of new agricultural centers (Milisauskas 2011b; Milisauskas and Kruk 2011a), diffusion of domesticated animals from West Asia to other regions. There developed the husbandry of sheep, goats and the first draught animals (Shnirelman 2012b; Meadows *et al*. 2007; see also Roberts 1998; Gupta 2004; Zeder and Hesse 2000; Bryner 2008). The active interchange of achievements (domesticates and their varieties, technologies, *etc.*) is observed (Zinkina *et al*. 2017, 2019). The first copper artefacts and tools in Egypt and Mesopotamia (and in Syria) date to this period (starting from the 5th millennium BCE) (Tylecote 1976: 9). According to Childe, the so-called urban revolution took place at that time (Childe 1952: ch. 7; see also Lamberg-Karlovsky and Sabloff 1979; Masson 1980; 1989: 33–41; Oppenheim 1968; Adams 1981; Pollock 2001: 45; Bernbeck and Pollock 2005: 17; Zablotska 1989: 34–38; Bondarenko 2006: 50; Mellaart 1975; Wenke 1990: 326–330; Turnbaugh *et al*. 1993: 464–465; Harris 1997: 146; Schultz and Lavenda 1998: 214–215; Balter 2006).[7]

[7] The formation of productive economies in Central Andes and Mesoamerica started in the 7th and 6th millennia BCE (see Berezkin 2007b, 2013: 17; Dillehay *et al.* 2010; Quilter *et al.* 1991; Vega-Centeno 2010).

During the *third* phase, from 5,000 to 3,500 BP, farming developed along with animal husbandry, crafts and trade which differentiated into separate branches of economy (we regard the third phase of the Craft-Agrarian production principle simultaneously as the final innovative phase of the Agrarian Revolution (about craft specialization see Costin 2005, 2015; Hruby and Flad 2007). Though, according to our theory, crafts did not determine the development of the Agrarian Revolution. One should note that according to some data, at the end of the second phase and beginning of the third one a very wide diffusion of major innovations (wheel, plough, pottery wheel, harness [yoke], and bronze metallurgy, *etc.*) was observed (Chubarov 1991; about plough see also in McNeill 1963: 24–25; Kramer 1965; Renfrew 2002; Bunch and Hellemans 2004; Milisauskas and Kruk 2011b) about bronze metallurgy see Tylecote 1976: 9; Chernykh 1992; Harding 2011; see also Duistermaat 2017; Roux 2017; Li Shuicheng 2018). This was the period when the first states, and later empires, rose in the Middle East. Urbanization also expanded reaching new regions (He Nu 2018; Chen Chun and Gong Xin 2018). This period ended with a major economic, agrotechnical, and craft upsurge in Egypt at the beginning of the New Kingdom (Vinogradov 2000).

The *fourth* phase (from 3,500 to 2,200 BP) is the period when systems of intensive (including non-irrigated plough) farming were developed in many parts of the world. We observe an unprecedented flourishing of crafts, cities, and trade, introduction and wide diffusion of iron metallurgy (Tylecote 1976; Chubarov 1991; Kolosovskaya and Shkunayev 1988: 211–212; Davies 2005: 61; Wells 2011), as well as the formation of new civilizations and other processes indicating that the new production principle was approaching its maturity. This phase lasted till the formation of new vast world empires from Rome in the West to China in the East (Chase-Dunn and Hall 1997; Chase-Dunn *et al*. 2010; Grinin 2010, 2011b; Grinin *et al*. 2016), which later led to major changes in productive forces and other social spheres.

The *fifth* phase (from 2,200 to 1,200 BP, *i.e.* 200 BCE to 800 CE) was the period of the most complete development of the productive forces of the craft-agrarian economy, the period of flourishing and disintegration of the ancient civilizations and formation of civilizations of a new type (Arab, European, *etc*. [Chase-Dunn and Hall 1997, 2011; Chase-Dunn and Manning 2002; Grinin 2011b]).

At the beginning of the sixth phase (800–1,430 CE, *i.e.* from the 9th century till the first third of the 15th century) one could observe important changes in the production and other spheres in the Arab-Islamic world and China; in particular, in the second half of the 1st century CE a wide international trade network from the East African Coast to South-East Asia and China was developed in the Indian Ocean basin (Bentley 1996; Chew Sing 2014, 2016; Boussac *et al.* 2016; about trans-Eurasian trade see Abu-Lughod 1989; about diffusion of innovations see Grinin and Korotayev 2015a; Grinin and Grinin 2015c). Later the urban and economic growth started in Europe, which had finally created the first industrial centers of and preconditions for the Industrial Revolution (see also Grinin and Korotayev 2013a, 2013b, 2015a).

2.4. The Trade-Industrial Production Principle

The first phase of the Trade-Industrial production principle may be dated to the period from the second third of the 15th century to the late 16th century (1430–1600; it means respectively the beginning of the initial phase of the Industrial Revolution). This phase includes those types of activities that were both more open to innovations and capable of accumulating more surplus (trade [see Mantoux 1929; Bernal 1965; Cameron 1989; see also Acemoglu *et al*. 2005; Goldstone 2009; Grinin and Korotayev 2015a] and colonial activities [see Baks 1986]), which had become more and more intertwined after the start of the 16th century. Besides, at that time, primitive industries (but still industries) developed in certain fields. It is during that period when, according to Wallerstein (1974, 1987), the capitalist world-economy originated.

It appears appropriate to mention here the viewpoint, according to which, along with the Industrial Revolution of the 18th century, there had also been an earlier industrial revolution (or even industrial revolutions). This technological upswing that took place in Europe between 1100 and 1600 was noticed long ago – back in the 1930s – starting with the work of Lewis Mumford (1934), Marc Bloch (1935), Eleanora Carus-Wilson (1941) and was actively studied by economic historians in around 1950–1980 (Lilley 1976; Forbes 1956; Armytage 1961; Gille 1969; White 1978; Gimpel 1992; for more details see also Hill 1955; Johnson 1955; Bernal 1965; Braudel 1973; Islamov and Freidzon 1986: 84; Gurevich 1969: 68; Dmitriev 1992: 140–141; Hoot 2010; see Lucas 2005). This period is also quite rightly considered as the time of scientific breakthrough, or rather a number of revolutionary breakthroughs in such areas as mathematics, astronomy, geography, cartography, *etc.* (see, *e.g.*, Singer 1941; Goldstone 2009). Though the idea of marking out Early Modern Period (the end of the 15th – 18th centuries) has attracted a number of supporters, however, all these scholars do not associate Early Modern Period with an earlier industrial revolution. Meanwhile it could give a great opportunity to deeper understand the logic of technological evolution as a whole.

Then the period between 1100 and 1450 may be regarded as a preparatory period of the Industrial Revolution with quite a vivid manifestation of early capitalist relations and forms of production in some regions of Europe (Northern Italy, Southern Germany, the Netherlands, Southern France [see, *e.g.*, Pirenne 1920–1932; Wallerstein 1974; Postan 1987; Milskaya and Rutenburg 1993; Lucas 2005; Grinin L. and Grinin A. 2015c, 2016; Grinin and Korotayev 2015a]).

The period from the second third of the 15th century to the end of the 16th century is the initial phase of the Industrial Revolution. It is associated with the development of navigation, engineering and mechanization on the basis of watermill, spreading and improving of different machines, the development of division of labor. At this time, in different parts of Europe, there are significant breakthroughs in different directions, which by the end of the period are synthesized into the general Western Europe system (Johnson 1955; Braudel 1973; Wallerstein 1974; Barg 1991; Yastrebitskaya 1993; Davies 1996; Grinin L. and Grinin A. 2015c, 2016; Grinin and Korotayev 2015a). The changes in one country tended to produce substantial impact on the economy and the lives of others – through the spread of innovations, through the publication of special technical books, through the movement of technical experts to different countries, through the introduction of various advances and innovations by kings and emperors to their realms, *etc.* Thus, we find impressive achievements in the field of mechanization in mining operations in Southern Germany and Bohemia; major contributions to the development of navigation, geographical discoveries and world trade accomplished by the Spanish and Portuguese, but also by the British; significant developments of technologies of manufacturing in Italian and Flemish cities; significant shifts in agriculture in Northern France and the Netherlands; important scientific and mathematical discoveries made by scientists in Italy, France, Poland, England; new financial technologies developed in Italy (Barone 1993; Davies 1996, 2001; Collins and Taylor 2006; Goldstone 2009, 2012; Ferguson 2011; Porter 2012). But all of this, anyway, quickly became the common heritage of Europe.

The period from the early 17th century to the first third of the 18th century (1600–1730) is the second phase of Trade-Industrial production principle (it can be also regarded as the middle phase of the Industrial Revolution). At that time one could observe the formation of a complex industrial sector and the capitalist economy, the increased mechanization and the deepening division of labor. This is the age of trade leadership of the Dutch, the successor to the hegemony of Spain and Portugal. The Netherlands created an unprecedented industry of shipbuilding, mechanized port facilities and fishing (Boxer 1965; Jones 1996; de Vries and van der Woude 1997; Rietbergen 2002; Israel 1995; Allen 2009; Goldstone 2009; Grinin L. and Grinin A. 2015c, 2016; Grinin and Korotayev 2015a). But the 17th century is a period of considerable changes in military technology and science, engineering; whereas as a result of wars and other processes the Netherlands lost its leadership, which was gradually moving to Britain (Rayner 1964; Boxer 1965; Snooks 1997; Jones 1996; de Vries and van der Woude 1997; Rietbergen 2002). So, during this phase of the Industrial Revolution (and new production principle) new industry sectors had become dominant in some countries (mostly in the Netherlands and Britain; about the development of innovations in different European countries in this period as well as in earlier and later ones see Grinin and Korotayev 2017).

Finally, the period between 1730 and 1830 may be identified as the third phase of Trade-Industrial production principle (and at the same time as the final phase of the Industrial Revolution). This breakthrough was accompanied by the creation of the sectors with a machine cycle of production and the use of steam power. Supplanting handwork with machines took place in cotton textile production that developed in Britain (Mantoux 1929; Berlanstein 1992; Mokyr 1993, 1999; Griffin 2010). Watt's steam engine started to be used in the 1760s and 1770s. A new powerful industry – machine production – had developed. The industrial breakthrough was more or less finalized in Britain in the 1830s. Although Britain was clearly the leader here, but we also observe in this period a number of important processes that can be identified as pan-European (including the development of military technology, trade, science, pan-European commercial and industrial crises of the second half of the 18th century, the beginning of the demographic revolution; see below). In this concept, we clearly see in the Industrial Revolution the result of the collective achievements of different societies of Europe, a sort of relay-race of achievements (see Grinin and Korotayev 2015a; Korotayev and Grinin 2017). The successes of industrialization were evident in a number of countries by that time and this was also accompanied by significant demographic transformations (Armengaud 1976; Minghinton 1976: 85–89; Chesnais 1992; Caldwell 2006; Dyson 2010; Livi-Bacci 2012).

The *fourth* phase (from the 1830s to the late 19th century [1830–1890]) is the period of the victory of machine production and its powerful diffusion (for more details see Grinin L. and Grinin A. 2015c, 2016). This period corresponded to the second technological system and/or techno-economic paradigm (railway lines, coal, steel) and the beginning of formation of the third one (electricity, chemical industry and heavy engineering).[8] This is a period of unbelievable number of innovations (see Bunch and Hellemans 2004; Korotayev and Grinin 2017).

The *fifth* phase (1890–1929) took place in the late 19th century − the early 20th century up to the world economic crisis of the late 1920s and 1930s.

[8] About the connection between Kondratieff waves and technological systems and/or techno-economic paradigms see Grinin *et al.* 2017a.

During that period significant changes took place (for more details see Grinin L. and Grinin A. 2015c, 2016). The chemical industries experienced rapid development including the production of human-made materials, a breakthrough was observed in steel production, the extensive use of electricity (together with oil) gradually began to replace coal. Electrical engines replaced the steam ones which therefore transformed factories as well as everyday life. The development of the internal combustion engine has led to the widespread use of automobiles. Due to the introduction of assembly line automobile manufacturing rose vigorously. It was a period of the first electronics innovations.

The *sixth* phase continued till the mid-20th century (1929–1955). The period of the 1930s gave a great number of basic innovations, many of which were implemented in 1940 – the 1970s. There were especially many achievements in the military sphere, aviation, in missile and later space rockets, in nuclei energy. It was a period of the great growth of automobile, chemical production and the beginning of electronic manufacturing including the first computers. A vigorous intensification of production and the introduction of scientific methods of its organization took place during this period. There was an unprecedented development of standardization and enlargement of production units. The signs of the forthcoming Cybernetic Revolution became more and more evident.

2.5. The Scientific-Cybernetic Production Principle and the Cybernetic Revolution

The Scientific-Cybernetic production principle is only at its beginning (see Figs 1, 2); only its first phase has been completed and the second phase still continues. Hence, all the calculations of the forthcoming phases' lengths are highly hypothetical (see Tables 1 and 2 below).

The *first* phase of the Scientific-Cybernetic production principle took place between the 1950s and mid-1990s, when a vigorous development of information technologies and the start of real economic globalization were observed. It is also connected with the transition to scientific methods in production and circulation management. Especially important changes took place in information technologies. In addition, this production revolution had a few other directions: in energy technologies, in synthetic materials production, automation, space exploration, and agriculture. However, its main results are still forthcoming.

As you know, the first phase of a new production principle corresponds to the initial phase of a new production revolution (see Fig. 1). The *production revolution* that began in the 1950s and continues up to the present in its early period was sometimes called the 'scientific-technical' revolution (*e.g.*, Bernal 1965; Benson and Lloyd 1983). However, in any case it would be more appropriate to call it the *Cybernetic Revolution* since its main changes will imply increasing opportunities to control various processes by means of self-regulated systems, *etc.*

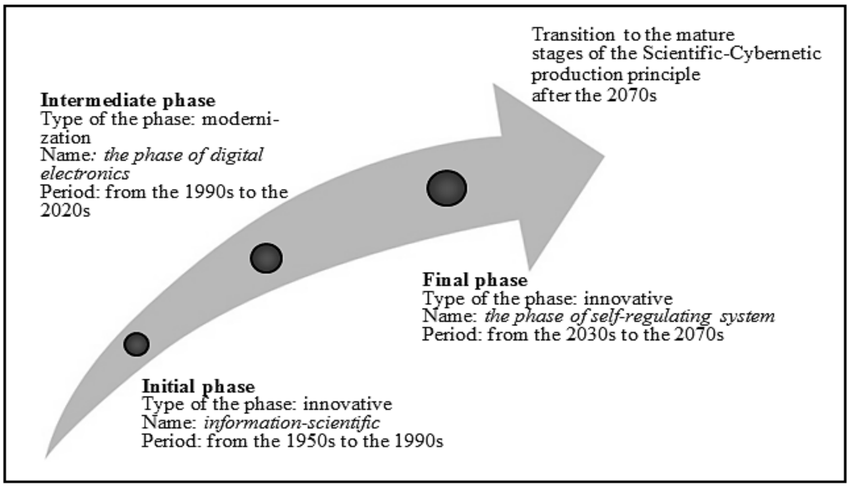

Fig. 1. The phases of the Cybernetic Revolution

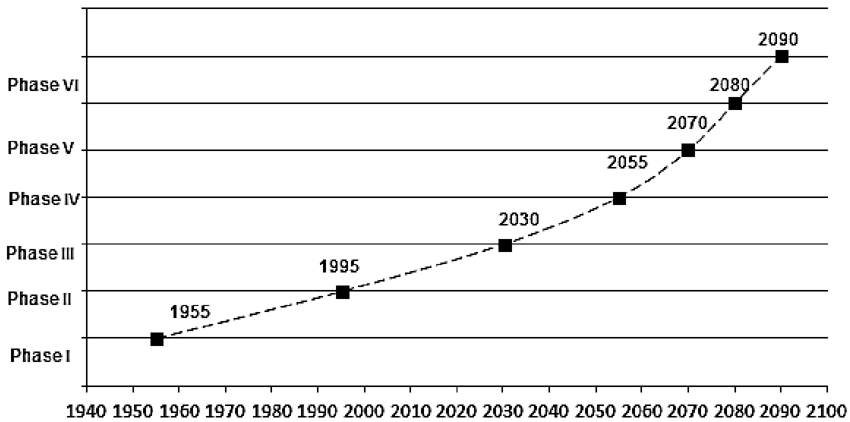

Fig. 2. The development of the Scientific-Cybernetic production principle

The *second* phase of the Scientific-Cybernetic production principle (= the intermediate phase of the Cybernetic Revolution, see Fig. 1) began in the mid-

1990s in conjunction with the development and wide diffusion of user-friendly computers, communication technologies, cell phones and so on. Medicine and biotechnologies have also made significant progress, as well as some other innovative fields (see Grinin L. and Grinin A. 2015a, 2015b, 2015c: part 3; 2016: Chs 3–4; Grinin L., Grinin A., and Korotayev 2017a). This phase continues up to the present.

Before we start to discuss the upcoming transformations, it is worth clarifying our understanding of modern and future technological progress rate. There are a number of scholars who believe that the rate of technological as well as scientific progress is already slowing down (Maddison 2007; Teulings and Baldwin 2014; Panov 2009; Phillips 2011; Korotayev and Bozhevolnov 2010). This can also be seen by comparing the number of inventions per decade in 1950 and 1960 with 1970 and 1990 according to the Bunch and Hellemans database (2004).

However, we do not think that in the future the rate of technological progress will gradually slow down nor that it will be constant. For the time period, which our theory allows us to predict, the speed will be nonlinear. At the first stage of the Cybernetic Revolution, the rate of technical progress accelerated, and at the second stage (at which we have been since the 1990s) it slowed down. We believe that this deceleration will not change until the mid-2030s – the beginning of the 2040s, and then the technological growth will experience a new acceleration. Then there will be a gradual slow-down up to the singularity point with the subsequent change of the pattern (see below).

The third phase of the Scientific-Cybernetic production principle is likely to begin approximately in the 2030s. It will mean the beginning of the final phase of the Cybernetic Revolution that in our view may become the epoch of 'self-regulating systems'. The final phase of this revolution may start in the sphere of medicine and will be connected with its innovative branches; thus, this will lead to serious modification of human organism and, perhaps, of its biological nature (for more details see Grinin L. and Grinin A. 2015c, 2016; Grinin, Korotayev, and Tausch 2016; Grinin L., Grinin A., and Korotayev 2017a).

The drivers of the final phase of the Cybernetic Revolution will be medical technologies, additive manufacturing (3D printers), nano- and bio- technologies, robotics, IT, cognitive technologies, which will together form a sophisticated system of self-regulating production. We can denote this complex as MANBRIC-convergence.[9] Among other technologies, medical will become the

[9] The order of the letters in the acronym does not reflect our understanding of the relative importance of areas of the complex. *E.g.*, biotechnologies will be more important than nanotechnologies, let alone additive manufacturing. The order is determined simply by the convenience of pronunciation.

main integrating part (see Grinin L. and Grinin A. 2015c, 2016; Grinin and Korotayev 2016a, 2016b; Grinin, Korotayev, and Tausch 2016; Grinin L., Grinin A., and Korotayev 2017a).

The expected lengths of the *fourth*, *fifth*, and *sixth* phases of the Scientific-Cybernetic production principle are 2055–2070; 2070–2080; 2080–2090, respectively (see Tables 1 and 2 below; for more details see Grinin 2006b).

The fourth phase implies that in the next two decades the sector of self-regulating systems will rapidly improve and diffuse to various regions at an enormous speed. MANBRIC-technologies will be finally formed and will occupy a central place in the new production principle. At the same time, this will be a period of significant growth in life expectancy and, accordingly (against the background of low fertility), a period of rapid global ageing that will also involve still 'young' regions, including sub-Saharan Africa and South Asia (Grinin L. and Grinin A. 2015c, 2016; Grinin, Korotayev, and Tausch 2016; Grinin L., Grinin A., and Korotayev 2017a, 2017b).

As we will see in the Section 5 the development of medical technologies and global ageing will be in a complex nonlinear dependence (see also Phillips 2011). At the third, but especially at the subsequent phases, there will be significant changes in the number of people employed in various professions, as well as major changes in the professions nomenclature, some of which will begin to disappear under the influence of new technologies (including robotization). In our opinion, unqualified services will be particularly at risk. At the same time the sphere of qualified and highly qualified services will undergo considerable transformation (for more details see Grinin L. and Grinin A. 2015c). There was a great deal of discussions about the future changes in professions. For example, most analysts predict extensive automation and robotization, including complete replacement of human labor in a number of professions (*e.g.*, Frey and Osborne 2017).

The fifth and sixth phases imply the beginning of the transition to a new economic system (see below) due to the increasing level of complexity of self-regulating systems and serious advances in medicine (see above). By this time, the process of global ageing will cover all countries. At the same time more conservative older population may influence innovation and its direction. This will be accompanied by profound painful changes and confrontations in societies within the World System. Also, there will be a growing number of social self-regulating systems that will mostly operate autonomously, regulating the behavior of a large number of people in certain situations. They can be used to create positive or negative behavioral stimuli (carrot and stick method) to regulate human behavior[10]. This will have fundamental and contradictory conse-

[10] Even today one can observe such regulatory systems, *e.g.*, car insurance, when a more accurate driver pays less. The system of total regulation of social behavior was announced in China sever-

quences, which can both appeal to the conservatism of the older generation or cause a contradictory reaction.

All this suggests that the period of the late 21st century and the early 22nd century will be decisive for human civilization. Fundamentally new socio-economical relationships will begin to emerge, the outlines of which are not clear yet. In this period, according to our estimation, the rate of technological progress will begin to slow down again. As a result, its pattern will change and besides the modern consumption model will start to change dramatically (see Conclusion). Thus, such a slowdown will mean that the old type of technological progress is beginning to transform into a new one, and, most likely, a transition to new forms of social relations will start.

3. Mathematical Interpretation of Technological Progress (in the Framework of Historical Process)

Introduction

The main objectives of this section are:

1. To show the duration of each of the four production principles and the duration of each of the six stages within one production principle. These data are presented in Tables 1 and 2.

In the tables one can see a) the general time parameters of the production principles; b) the acceleration of technological evolution both within a production principle from one stage to another, as well as comparison with the previous and subsequent production principles; c) presented data allow us to summarize the technological narrative and chronological description of historical process, which we gave in the previous section.

2. To show that production principle is not just a certain stage of development of the world-systemic productive forces, but a rather complex cycle of technical innovations and organizational-technological system rearrangements of manufacturing. It inevitably, on the one hand, requires changes in various spheres of society, but, on the other hand, brings new changes. Tables 3 and 4 show the calculations of the relationships between the stages (and combinations of the stages) within each production principle and demonstrate that each cycle of the production principle retains surprising consistency, which cannot be accidental. For example, the duration of the first stage of each production principle in per cent of the total duration of the entire production principle ranges from 28 to 33 %. Recall that these are one of the most important stages of the production revolutions. The ratio of the duration of stages to each other is also quite close, for example, in all four production principles, the ratio varies in a rather

al years ago and is already being introduced (see Chin and Wong 2016). URL: https://www.wsj.com/articles/chinas-new-tool-for-social-control-a-credit-rating-for-everything-1480351590.

narrow framework. There are a small scatter of proportions, oscillating around a certain in all 19 ratios given in Tables 3 and 4. These stable ratios demonstrate certain deep and fundamental patterns of technological development and technological evolution in the framework of the historical process. All this allows us to make some predictions about the duration of the future stages of the Scientific-Cybernetic production principle.

3. To calculate the acceleration of technological progress, the results of which will be presented below. This section therefore prepares the basis for the conclusions of the following sections.

Table 1 presents dates for all the phases of all the production principles. However, it should be taken into account that for convenience in chronology all dates are averaged. The absolute lengths of the phases in thousands of years are presented in Table 2.

Table 1. Chronology of production principle phases (figures before brackets correspond to absolute datings (BP); figures in brackets – to years BCE. Bold figures indicate phase lengths (in thousands of years)

Production principle	**1st phase**	**2nd phase**	**3rd phase**	**4th phase**	**5th phase**	**6th phase**	**Overall for production principle**
1. Hunter-Gatherer	40,000–30,000 BP (38 000–28 000 BCE) **10**	30,000–22,000 (28 000–20 000 BCE) **8**	22,000–17,000 (20 000–15 000 BCE) **5**	17,000–14,000 (15 000–12 000 BCE) **3**	14,000–11,500 (12 000–9500 BCE) **2.5**	11,500–10,000 (9500–8000 BCE) **1.5**	40,000–10,000 (38 000–8000 BCE) **30**
2. Craft-Agrarian	10,000–7,300 (8,000–5,300 BCE) **2.7**	7,300–5,000 (5,300–3,000 BCE) **2.3**	5,000–3,500 (3,000–1,500 BCE) **1.5**	35,000–2,200 (1,500–200 BCE) **1.3**	2,200–1,200 (200 BCE–800 CE) **1.0**	800 CE–1,430 CE **0.6**	10,000–570 (8,000 BCE – 1,430 CE) **9.4**
3. Trade-Industrial	1430–1600 **0.17**	1600–1730 **0.13**	1730–1830 **0.1**	1830–1890 **0.06**	1890–1929 **0.04**	1929–1955 **0.025**	1430–1955 **0.525**
4. Scientific-Cybernetic	1955–1995* **0.04**	1995–2030 **0.035**	2030–2055 **0.025**	2055–2070 **0.015**	2070–2080 **0.01**	2080–2090 **0.01**	1955–2090 **0.135–0.160**

Note: Starting from the second column of the row we give our estimates of the expected lengths of the Scientific-Cybernetic production principle phases.

Table 2. Production principles and their phase lengths (in thousands of years)

Production principle	**1st phase**	**2nd phase**	**3rd phase**	**4th phase**	**5th phase**	**6th phase**	**Overall for production principle**
1. Hunter-Gatherer	10	8	5	3	2.5	1.5	30
2. Craft-Agrarian	2.7	2.3	1.5	1.3	1.0	0.6	9.4
3. Trade-Industrial	0.17	0.13	0.1	0.06	0.04	0.025	0.525
4. Scientific-Cybernetic	0.04	0.035*	0.025	0.015	0.01	0.01	0.135

Note: * This row indicates our estimates of the expected lengths of the Scientific-Cybernetic production principle phases.

Thus, the proposed periodization demonstrates stable patterns of recurrent developmental cycles with a shortening of the period (each of which includes six phases); however, *each subsequent cycle was shorter than the previous one due to the acceleration of technological growth.* Note that these are recurrent cycles, because within each cycle in some respect the development follows the same pattern: every phase within every cycle plays a functionally similar role; what is more, the proportions of the lengths of the phases and their combinations remain rather stable (see Tables 3 and 4). All this is confirmed by calculations in Tables 3 and 4 according to which stable proportions of phase lengths and their combinations remain intact with the change of production principles.

Table 3 presents the results of our calculations of the ratio of each phase's length to the length of the respective production principle using a rather simple methodology. The absolute length of a phase (or a sum of the lengths of two or three phases) is divided by the full length of the respective production principle. For example, if the length of the Hunter-Gatherer production principle is 30,000 years, the duration of its first phase is 10,000, the second is 8,000, and the duration of the third is 5,000. The ratio of the first phase length to the total production principle length will be 33.3 %; the ratio of the sum of the first and the second phases' lengths to the total production principle length will be 60 %; and the ratio of the sum of the first, the second, and the third phases' lengths to the total production principle length will be 76.7 %.

Table 4 employs an analogous methodology to compare lengths of phases (and combinations of phases) within one production principle. For example, for the Hunter-Gatherer production principle the ratio of the first phase length (10,000 years) to the second one (8,000 years) equals 125 %; whereas the ratio of the second phase to the third one (5,000 years) is 160 %. In the meantime, the ratio of the sum of the first and the second phases' lengths to the sum of the third and the fourth phases (3,000 years) equals 225 %.

Tables 3 and 4 also present the average rates for all the production principles.

Table 3. Ratio of each phase (and phase combination) length to the total length of respective production principle (%)

Production principle	1	2	3	4	5	6	1–2	3–4	5–6	1–3	4–6
1. Hunter-Gatherer	33.3	26.7	16.7	10	8.3	5	60	26.7	13.3	76.7	23.3
2. Craft-Agrarian	28.7	24.5	16.0	13.8	10.6	6.4	53.2	29.8	17	69.1	30.9
3. Trade-Industrial	32.4	24.8	19	11.4	7.6	4.8	57.1	30.5	12.4	76.2	23.8
4. Scientific-Cybernetic	29.6	25.9	18.5	11.1	7.4	7.4	55.6	29.6	14.8	74.1	25.9
Average	31	25.5	17.6	11.6	8.5	5.9	56.5	29.2	14.4	74.0	26.5

Table 4. Comparison of phase length ratios for each production principle (%)

Production principle	1:2	2:3	3:4	4:5	5:6	(1+2):(3+4)	(3+4):(5+6)	(1+2+3):(4+5+6)
1. Hunter-Gatherer	125	160	166.7	120	166.7	225	200	328.6
2. Craft-Agrarian	117.4	153.3	115.4	130	166.7	178.6	175	224.1
3. Trade-Industrial	130.8	130	166.7	150	160	187.5	246.2	320
4. Scientific-Cybernetic	114.3	140	166.7	150	100	187.5	200	285.7
Average	121.4	144.2	149.7	133.3	160.9	190.3	205.3	282.1

So, our quantitative analysis represented in tables above indicates the following points: a) evolution of each production principle in time has recurrent features; there are stable mathematical proportions between the lengths of phases and phase combinations within each production principle (Tables 3 and 4); b) the cycle analysis clearly indicates that the technological development rate increases sharply just as a result of production revolutions; c) the analysis of stable proportions of production principle cycles makes it possible to propose some tentative forecasts (in particular, with respect to the lengths of the future phases of the fourth production principle).

4. Mathematical Interpretation of the Technological Progress, Methodology and Calculations

Each production principle is a six-phase cycle. The beginning of each phase can be considered as an important technological shift or phase transition. As a result of our periodization, 24 phases and, respectively, 23 phase transitions have been identified (see Table 5). The chronology of the identified phases is presented below in the same table.

As a rule, complex and long-term processes cannot proceed evenly. This fully applies to technological evolution. As already noted, technological progress is a series of accelerations and decelerations in the speed of technological development. There is an idea that the mechanism of such rhythms is associated with the slowdown of progress due to constant obstacles, such as lack of knowledge (Kayal 1999). Of course, in general this is true. However, according to our theory, the acceleration and deceleration of technological progress depends on the functional features of each time phase within a super-long cycle of technological changes (or a production principle). At some stages there is a kind of 'explosion' of innovations, where one can see acceleration of the technological progress (*e.g.*, the first and third stages of production principle), at others – these innovations are improving and spreading, thus slowing down (*e.g.,* at the second stage of the production principle). At some stages (*e.g.*, the fifth one) a powerful expansion of the production principle occurs, at others under the influence of crises, a slowdown is observed (the last – sixth – stage).

To calculate the technological growth rate, we apply the methodology proposed by Alexander Panov (2004, 2005a, 2005b, 2006, 2008, 2009, 2011, 2013, 2017), according to which the temporal distance between phase transitions (=temporal length of the phases) is recalculated into the frequency of phase transitions = number of phase transitions = macroevolutionary growth rate. In Panov's case this was the speed of planetary macroevolutionary development; in our case this variable can be well interpreted as the technological growth rate within historical process (or it can also be called macrotechnological growth). It is noticeable that, as in Panov's time series (like in similar time series of Theodore Modis [2002, 2003], Raymond Kurzweil [2001, 2005] and David LePoire [2009, 2013]; see Korotayev 2018 for an analysis of these time series), the temporal length of phases in our time series systematically decreases, whereas the macrotechnological growth rate increases in a similarly systematic way following a rather remarkable pattern (see Table 5).

4.1. Calculation of the Singularity with the Incompleteness of the Scientific-Cybernetic Production Principle

It is important to note that the singularity does not indicate the point where the value of the respective variable actually becomes infinite. It rather indicates the point before which the hyperbolic shape of the respective curve should change to some different trajectory *implying a certain slowdown* of the respective processes that have been observed in recent decades (Huebner 2005; LePoire 2005; Phillips 2011; Korotayev 2018). Below we will discuss the possibility of a new acceleration of technological growth.

We believe that the calculation of the singularity can be done both with the empirically observed data only, and using some theoretically predicted data points, as far as we can anticipate the technological development. That is why we use a dual approach to determining the singularity. In the first case, we show that if we use our days as the last point for calculations, the result will be close to what Kurzweil, Modis, and Panov have, which shows that our mathematical apparatus is quite adequate. However, only a mathematical apparatus without an essential theoretical part is obviously not enough. And since we – hopefully – have convincingly proved that the slowdown and acceleration of the technological process occur cyclically, we give below the calculation of the singularity in accordance with the forecast of the expected acceleration of the technological process after the 2030s and the 2040s. And this calculation constitutes the main part of our paper.

Table 5. Production principle phases, their dates, lengths and dynamics of technological growth rate (for the empirically observed data points only)

Production Principle Phases	Date of The Phase Start	Phase Length (Years)	Macrotechnological Growth Rate (Frequency of Phase Transitions per Year)
Hunter-Gatherer 1	40,000 BP	10,000	1.0×10^{-4}
Hunter-Gatherer 2	30,000 BP	8,000	1.3×10^{-4}
Hunter-Gatherer 3	22,000 BP	5,000	2.0×10^{-4}
Hunter-Gatherer 4	17,000 BP	3,000	3.3×10^{-4}
Hunter-Gatherer 5	14,000 BP	2,500	4.0×10^{-4}
Hunter-Gatherer 6	11,500 BP	1,500	6.7×10^{-4}
Craft-Agrarian 1	10,000 BP	2,700	3.7×10^{-4}
Craft-Agrarian 2	5,300 BCE	2,300	4.3E-04
Craft-Agrarian 3	3,000 BCE	1,500	6.7E-04
Craft-Agrarian 4	1,500 BCE	1,300	7.7E-04
Craft-Agrarian 5	200 BCE	1,000	1.0E-03
Craft-Agrarian 6	800 CE	630	1.6E-03
Trade-Industrial 1	1430	170	5.9E-03
Trade-Industrial 2	1600	130	7.7E-03

Continuation of the Table

Production Principle Phases	Date of The Phase Start	Phase Length (Years)	Macrotechnological Growth Rate (Frequency of Phase Transitions per Year)
Trade-Industrial 3	1730	100	1.0E-02
Trade-Industrial 4	1830	60	1.7E-02
Trade-Industrial 5	1890	39	2.6E-02
Trade-Industrial 6	1929	26	3.8E-02
Scientific-Cybernetic 1	1955	40	2.5E-02
Scientific-Cybernetic 2	1995		

The graphic presentation of the macrotechnological growth rate detected in our time series looks as follows (see Fig. 3):

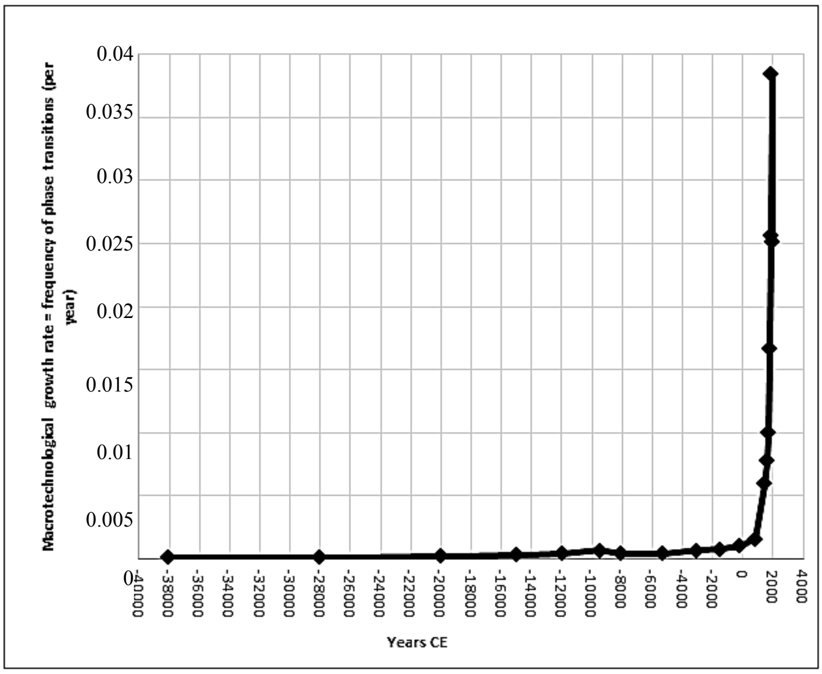

Fig. 3. Dynamics of the global macro technological growth rate (= frequency of phase transitions per year), 40,000 BP to the late 20th century

It is not difficult to see that the general shape of the resultant curve is unmistakably hyperbolic, whereas as it is well known the hyperbolic function has an explicit mathematical singularity.

Let the X-axis represent the time before the singularity (whereas the Y-axis will represent the technological growth rate) and calculate the singularity date by getting such a hyperbolic curve that would describe our time series in the most accurate way. The results of this analysis are presented in Fig. 4 (note that our mathematical analysis has identified the singularity date for this time series as 2018 CE).

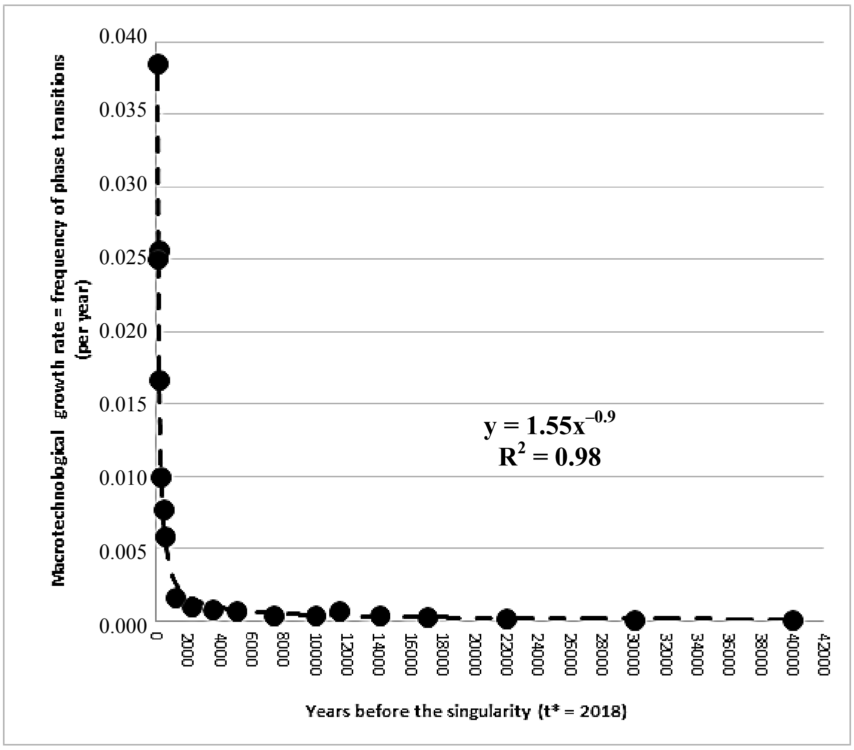

Fig. 4. Scatterplot of the phase transition points described in Table 5 with the fitted power-law regression line – for the singularity date identified as 2018 CE with the least squares method (natural scales)

Below the same figure is presented in the double logarithmic scale (see Fig. 5):

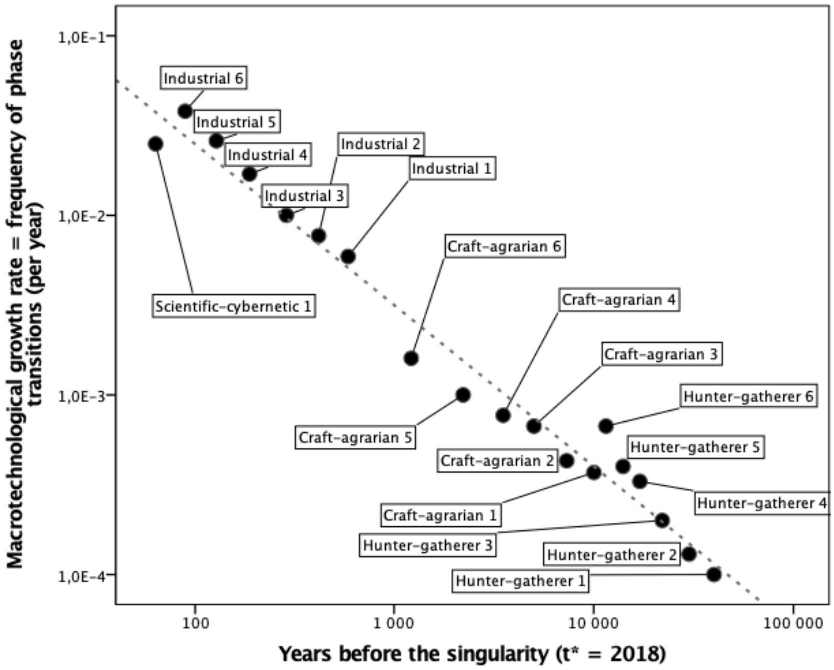

Fig. 5. Scatterplot of the phase transition points described in Table 5 with the fitted power-law regression line – for the singularity date identified as 2018 CE with the least squares method (double logarithmic scale)

Let us now analyze the results. As we see, our power-law regression on the technological growth phase transitions data points presented above in Table 5 has identified the following best fit equation describing this time series in a rather accurate (R^2 = 0,98) way:

$$V_t = \frac{1,55}{x^{0,9}}, \qquad \text{(Eq. 1)}$$

where V_t is the global macrotechnological development rate, x is the time remaining till the singularity, and 1,55 and 0,9 are constants.

Note that the denominator's exponent (0,9) turns out to be not so much different from 1; hence, there are some grounds to use this equation in the following simplified form:

$$V_t = \frac{1,55}{x}, \tag{Eq. 2}$$

where V_t is the global macrotechnological development rate, x is the time remaining till the singularity, and 1,55 is a constant.

Of course, x (the time remaining till the singularity) at the moment of time t equals $t^* – t$, where t^* is the time of singularity, Thus,

$$x = t^* – t.$$

Hence, Eq. 2 can be rewritten in the following way:

$$V_t = \frac{1,55}{t^* - t}, \tag{Eq. 3}$$

where V_t is the global macrotechnological development rate at time t, t^* is the time of singularity, and 1,55 is a constant.

Finally, let us recollect that our least squares analysis of the phase transition points described in Table 5 has identified the singularity date as 2018 CE. Thus, Eq. 3 can be further re-written in the following way:

$$V_t = \frac{1,55}{2018 - t}. \tag{Eq. 4}$$

Of course, in a more general form it should be written as follows:

$$V_t = \frac{C}{t^* - t}, \tag{Eq. 5}$$

where C and t^* are constants.

Note that algebraic equation of the type

$$y_t = \frac{C}{t^* - t} \tag{Eq. 5}$$

can be regarded as solution of the following differential equation:

$$\frac{dy}{dt} = \frac{y^2}{C} \tag{Eq. 6}$$

(see, *e.g.*, Korotayev, Malkov, and Khaltourina 2006a: 118–120).

Thus, the acceleration pattern implied by Eq. 4 can be spelled out as follows:

$$\frac{dV}{dt} = \frac{V^2}{1,55} \approx 0,65V^2. \tag{Eq. 7}$$

Thus, the overall pattern of acceleration of global technological growth rate that described rather accurately the technological growth phase transitions data points presented above in Table 5 with model (4) / (5) can be spelled out as follows: throughout most of the human history (at least since the Upper Paleolithic Revolution) the increase in macrotechnological growth rate a times tended to be accompanied by a^2 increase in its acceleration speed; thus, a twofold increase in macrotechnological development rate tended to be accompanied by a fourfold increase in the acceleration speed of this development rate; an increase in macrotechnological development rate ten times tended to be accompanied by 100 times increase in the acceleration speed of this development rate; and so on. The past tense was used in the statement above, because the global technological growth does not appear to have followed this pattern in the recent decades due to the abovementioned slowdown (otherwise, incidentally, it would have become infinite already last year). On the other hand, below we will discuss the possibility and implications of a new acceleration of global technological growth.

4.2. Notes about Acceleration Patterns

Note that a rather similar acceleration pattern has been earlier detected for the Modis – Kurzweil series of 'canonical milestones / complexity jumps' (Modis 2002, 2003; Kurzweil 2005) as well as Panov series of 'global phase transitions / biospheric revolutions' (Panov 2005b, 2017; Korotayev 2018). Incidentally, Modis – Kurzweil series started with the origin of Milky Way 10 billion years ago and ended with the emergence of Internet and human genome sequencing around 1995, whereas Panov series began with the origin of life on the Earth 4×10^9 years ago and ended with Information globalization dated by Panov to 1991 CE.

Indeed, the acceleration pattern detected in the Modis – Kurzweil series is described with 99.89 % accuracy by the following equation:

$$y = \frac{2,054}{(2029 - t)^{1,003}}, \qquad \text{(Eq. 8)}$$

where y is the global macrodevelopment rate (number of phase transitions per a unit of time), and 2029 CE is the best-fit singularity point estimate.

The simplified version of this model looks as:

$$y_t = \frac{2,054}{2029 - t}, \qquad \text{(Eq. 9)}$$

whereas algebraic expression can be regarded as a solution for the following differential equation:

$$\frac{dy}{dt} = \frac{y^2}{2,054} \approx 0,5y^2. \qquad \text{(Eq. 10)}$$

On the other hand, the acceleration pattern detected in the Panov series is described with 99.91 % accuracy by the following equation (Korotayev 2018):

$$y = \frac{1,886}{\left(2027 - t\right)^{1,01}}. \quad \text{(Eq. 11)}$$

The simplified version of this model looks as:

$$y = \frac{1,9}{2027 - t}, \quad \text{(Eq. 11)}$$

whereas such an algebraic equation can be regarded as a solution of the following differential equation that is very similar to the one that we obtained above for the Modis – Kurzweil series, as well as for our series of technological phase transitions:

$$\frac{dy}{dt} = \frac{y^2}{1,9} \approx 0,5y^2. \quad \text{(Eq. 12)}$$

As we can see, all the three series are described accurately by very similar mathematical models with very similar parameters, including *t** (the singularity time point).

In fact, this is not entirely surprising. Indeed, Panov's list of 'biospheric revolutions' / 'phase transitions' since the Upper Palaeolithic Revolution looks as follows (Panov 2005b: 221):

11. The Upper Palaeolithic revolution (40 x10^3 years ago).

12. Neolithic revolution [Agrarian revolution[11]] (12–9 x 10^3 years ago).

13. Urban revolution (the beginning of the Ancient world) (4,000–3,000 BC).

14. Imperial antiquity, Iron age, the revolution of the Axial time (750 BC). The appearance of a new type of state formations – empires, and a culture revolution, new kinds of thinkers such as Zaratushtra, Socrates, Budda, and others.

15. The beginning of the Middle Ages (500 CE).

16. The beginning of the Modern period, the first industrial revolution [the initial phase of the Industrial revolution] (1500 CE).

17. The second industrial revolution (steam and electricity), [the beginning of the stage of maturity and expansion of the Trade-Industrial production principle] (1830).

18. Information revolution, the beginning of the postindustrial epoch [the initial phase of the Cybernetic Revolution] (1950).

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[11] In the square brackets we put the names of phase transitions from our periodization, which correspond with periods by Panov.

As one can see, in the description of 7 out of 8 'biospheric' revolutions identified by Panov, he explicitly mentions major technological breakthroughs associated with them. The same is more or less true with respect to the Modis – Kurzweil series (Modis 2002, 2003; Kurzweil 2005). Thus, for the both series with respect to the period after 40,000 BCE canonical milestones / complexity jumps / global phase transitions / biospheric revolutions are very strongly identified with major technological breakthroughs / phase transition. Thus, it is hardly surprising that the acceleration patterns detected both in these two series and in our series of phase transitions turn out to be very similar indeed. On the other hand, it is very remarkable that the pattern of the technological growth rate acceleration detected for the period after 40,000 BP fits so well the pattern of the acceleration of planetary macroevolution identified for the period since the origins of life on our planet and till the Upper Paleolithic Revolution.[12]

It is also important to mention that in their famous article published in the journal *Science* in 1960 von Foerster, Mora, and Amiot presented their results of the analysis of the world population growth pattern. They showed that between 1 and 1958 CE the world's population (N) dynamics can be described in an extremely accurate way with the following astonishingly simple equation:

$$N_t = \frac{C}{(t^* - t)^{0.99}}, \qquad \text{(Eq. 13)}$$

where N_t is the world population at time t, and C and t^* are constants, with t^* corresponding to the so-called 'demographic singularity'. Parameter t^* was estimated by von Foerster and his colleagues as 2026,87 which corresponds to November 13, 2026; this made it possible for them to supply their article with a public-relations masterpiece title *Doomsday: Friday, 13 November, A.D. 2026* (von Foerster, Mora, and Amiot 1960). Note that von Foerster and his colleagues detected the hyperbolic pattern of world population growth for 1 CE – 1958 CE; later it was shown that this pattern continued for a few years after 1958, and also that it can be traced for many millennia BCE (Kapitza 1996; Kremer

[12] Actually, we had some grounds to expect that the planetary macroevolutionary acceleration in the last four billion years (including the acceleration of technological growth rate after 40,000 BP) could be described by a single hyperbolic equation quite accurately, because our earlier research found that both biological and social macroevolution could be described by rather similar simple hyperbolic equations (Korotayev 2005, 2006a, 2006b, 2007a, 2007b, 2008, 2009, 2012, 2013; Korotayev and Khaltourina 2006; Khaltourina *et al.* 2006; Khaltourina and Korotayev 2007; Korotayev, Malkov, and Khaltourina 2006a, 2006b; Markov and Korotayev 2007, 2008; Markov, Anisimov, and Korotayev 2010; Korotayev and Malkov 2012; Korotayev and Markov 2014, 2015; Grinin, Markov, and Korotayev 2013, 2014, 2015; Korotayev and Malkov 2016; Korotayev, Zinkina, and Andreev 2016; Korotayev and Zinkina 2017), but one should note that even we were really astonished to find such a close fit.

1993; Tsirel 2004; Podlazov 2000, 2017; Korotayev, Malkov, and Khaltourina 2006a, 2006b). In fact, Kremer (1993) claims that this pattern is traced since 1,000000 BP, whereas Kapitza (1996, 2003, 2006, 2010) even insists that it can be found since 4,000000 BP.

It is hard not to notice that the world population growth acceleration pattern, detected by von Foerster in the empirical data on the world population dynamics between 1 and 1958, turns out to be virtually identical with the one that has been detected above with respect to our series of technological phase transitions describing the global technological growth rate acceleration (as well as for both Modis – Kurzweil and Panov series describing the planetary macroevolutionary development acceleration).

Actually, the fact that the equation which describes the dynamics of world population so well turns out to be so close to the dynamics of the global technological growth rate is not really surprising. Indeed, it implies that in the long term the global technological growth rate should be proportional to the global population. However, as has been demonstrated by Taagepera (1976, 1979), Kremer (1993), Podlazov (2000, 2017), and Tsirel (2004), the global technological growth rate *is*, indeed, proportional to the global population.

For example, Michael Kremer notes that the 'high population spurs technological change because it increases the number of potential inventors…[13]. All else equal, each person's chance of inventing something is independent of population. Thus, in a larger population there will be proportionally more people lucky or smart enough to come up with new ideas' (Kremer 1993: 685); thus, 'the growth rate of technology is proportional to total population' (*Ibid.*: 682).

Thus, both the theory developed by Taagepera, Kremer, Podlazov, Tsirel, and the fact that our best-fit equation for the dynamics of global technological growth rate turns out to be almost identical with von Foerster's equations describing dynamics of the world population suggest that the global technological growth rate should in long term be proportional to the world population. In fact, our empirical text has supported this hypothesis – world population estimates of Kremer demonstrate a very high and significant (r = 0,928; p < 0,001) correlation with our estimates of the global technological growth rate presented above in Table 5 (see Fig. 6):

[13] Kremer notes that 'this implication flows naturally from the nonrivalry of technology… The cost of inventing a new technology is independent of the number of people who use it. Thus, holding constant the share of resources devoted to research, an increase in population leads to an increase in technological change' (Kremer 1993: 681).

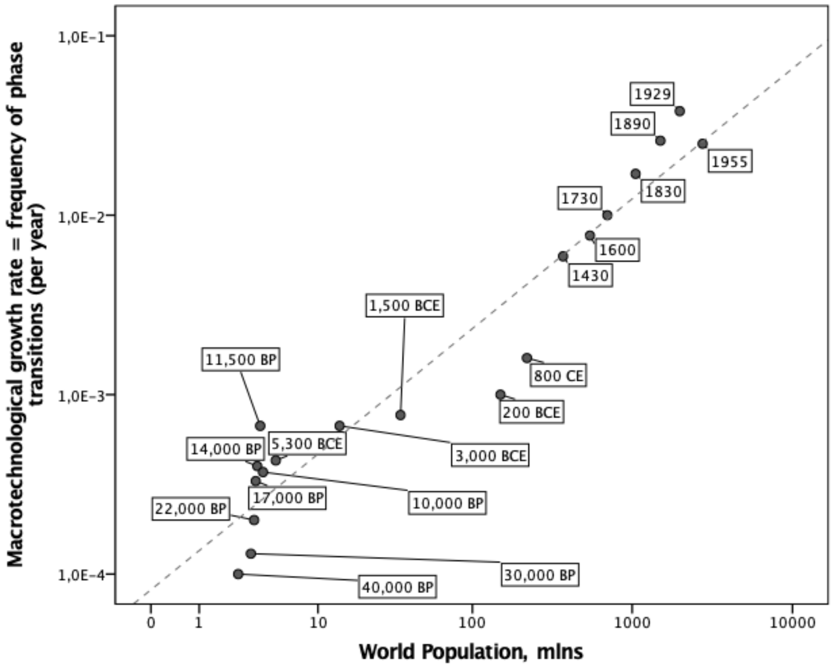

Fig. 6. Correlation between the world population (millions) and the global technological growth rate, double logarithmic scale, r = 0,928; p < 0,001

Source: Kremer 1993: 683.

4.3. Calculation of the Singularity, Taking into Account the Predicted Phases of the Scientific-Cybernetic Production Principle

As mentioned above, there are different ways to estimate the singularity point in respect of theoretical approaches to forecast the future of development of technological progress. Note that Eq. 1 (see above) has been calculated on the basis of the empirically observed data points only. However, the theory of production principles allows forecasting a few more data points.

Indeed, we have shown above that there are grounds to expect that the *second* phase of the Scientific-Cybernetic production principle (= the intermediate phase of the Cybernetic Revolution) that began in the mid-1990s will continue till around 2030 when there are grounds to expect the third phase, which will mean the beginning of the final phase of the Cybernetic Revolution, that in our view may become the epoch of 'self-regulating systems', that is, the vast expansion of opportunities to purposefully influence and direct various natural and production processes. It is expected to continue till around 2055 when there are grounds to forecast the start of the fourth phase that implies that the formed sector of self-regulating systems will rapidly improve over the next two decades and will diffuse to various regions at an enormous speed. At the same time, this should be a period of significant growth in life expectancy. The duration of the last two phases has been estimated above to be around 20 years. This allows adding to the list of empirically estimated data points a few forecasted ones, which results in Table 6.

Table 6. Production principle phases, their dates, lengths and dynamics of technological growth rate (for the empirically observed and forecasted data points)

Production Principle Phases	Date of the Phase Start	Phase Length (Years)	Macrotechnological Growth Rate (Frequency of Phase Transitions per Year)
Hunter-Gatherer 1	40,000 BP	10,000	1.0×10^{-4}
Hunter-Gatherer 2	30,000 BP	8,000	1.3×10^{-4}
Hunter-Gatherer 3	22,000 BP	5,000	2.0×10^{-4}
Hunter-Gatherer 4	17,000 BP	3,000	3.3×10^{-4}
Hunter-Gatherer 5	14,000 BP	2,500	4.0×10^{-4}
Hunter-Gatherer 6	11,500 BP	1,500	6.7×10^{-4}
Craft-Agrarian 1	10,000 BP	2,700	3.7×10^{-4}
Craft-Agrarian 2	5,300 BCE	2,300	4.3E-04
Craft-Agrarian 3	3,000 BCE	1,500	6.7E-04
Craft-Agrarian 4	1,500 BCE	1,300	7.7E-04
Craft-Agrarian 5	200 BCE	1,000	1.0E-03
Craft-Agrarian 6	800 CE	630	1.6E-03
Trade-Industrial 1	1430	170	5.9E-03
Trade-Industrial 2	1600	130	7.7E-03
Trade-Industrial 3	1730	100	1.0E-02
Trade-Industrial 4	1830	60	1.7E-02
Trade-Industrial 5	1890	39	2.6E-02
Trade-Industrial 6	1929	26	3.8E-02
Scientific-Cybernetic 1	1955	40	2.5E-02
Scientific-Cybernetic 2	1995	35	2.9E-02
Scientific-Cybernetic 3	2030	25	4.0E-02
Scientific-Cybernetic 4	2055	15	6.7E-02
Scientific-Cybernetic 5	2070	10	1.0E-01
Scientific-Cybernetic 6	2080		

A mathematical analysis of the resultant time series yields the following results (see Fig. 7):

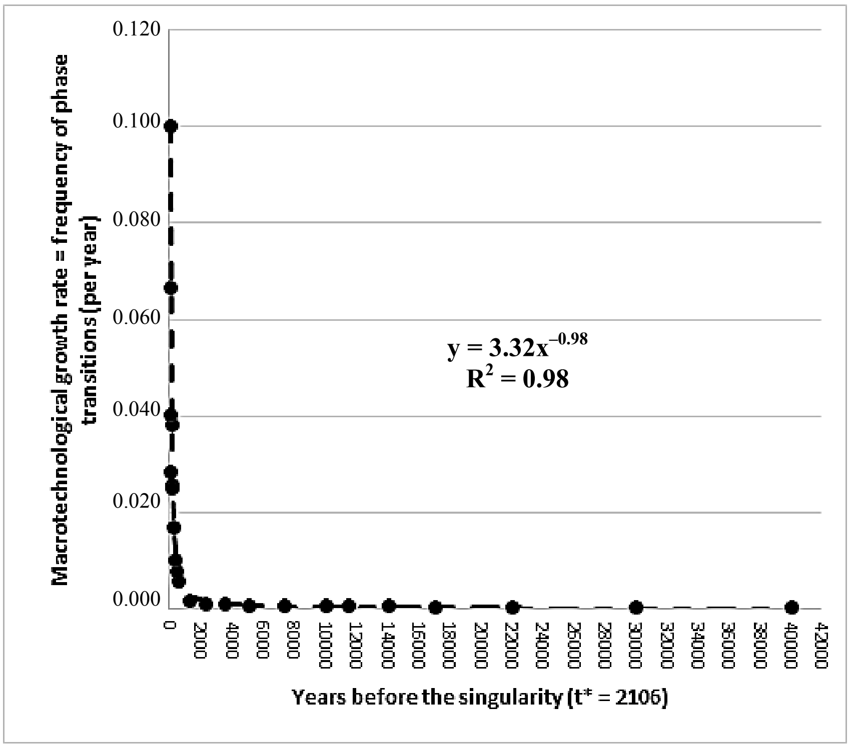

Fig. 7. Scatterplot of the phase transition points (both empirically estimated and forecasted) described in Table 6 with the fitted power-law regression line; for the singularity date identified as 2106 CE with the least squares method (natural scales)

Below the same figure is presented in the double logarithmic scale (see Fig. 8).

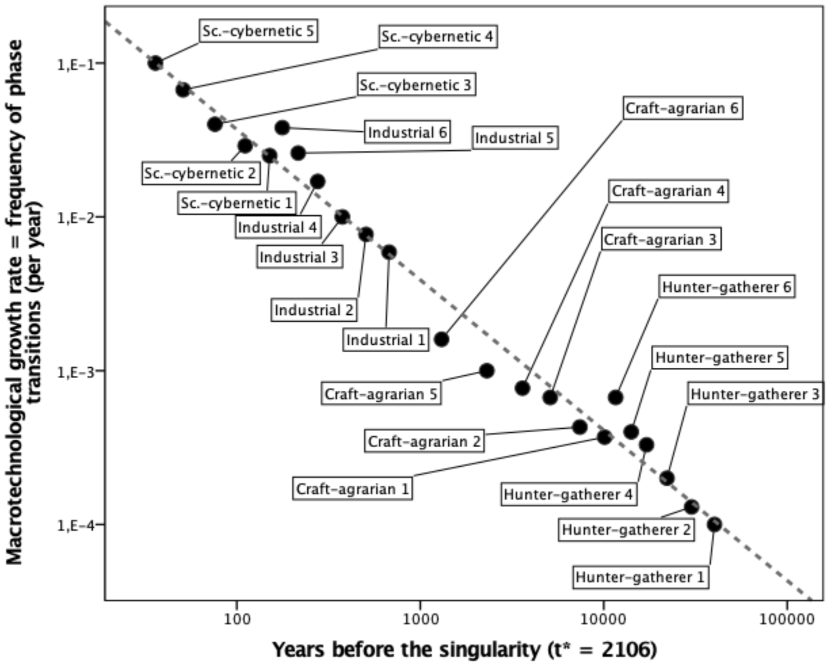

Fig. 8. Scatterplot of the phase transition points (both empirically estimated and forecasted) described in Table 6 with the fitted power-law regression line); for the singularity date identified as 2106 CE with the least squares method (double logarithmic scale)

Let us now analyze these new results. As we see, our power-law regression on the technological growth phase transitions data points presented above in Table 6 (that includes four forecasted data points on the basis of the assumed new wave of acceleration of the global macrotechnological growth rate forecasted by the theory of production principles) has identified the following best-fit equation describing this time series in a rather accurate (R^2 = 0,98) way:

$$V_t = \frac{3,32}{x^{0,98}}, \qquad \text{(Eq. 14)}$$

where V_t is the global macrotechnological development rate, x is the time remaining till the singularity, and 3,32 and 0,98 are constants.

Note that the denominator's exponent (0,98) turns out to be much closer to 1 than in the case with Eq. 1; hence, there are even more grounds to use this equation in the following simplified form:

$$V_t = \frac{3{,}32}{x}, \qquad \text{(Eq. 15)}$$

where V_t is the global macrotechnological development rate, x is the time remaining till the singularity, and 3,32 is a constant.

Finally, as our least-squares analysis of the phase transition points described in Table 6 has identified the singularity date as 2106 CE, Eq. 15 can be further re-written in the following way:

$$V_t = \frac{3{,}32}{2106 - t}. \qquad \text{(Eq. 16)}$$

Thus, if our forecast based on the theory of production principles is justified, there are grounds to expect that the global macrotechnological growth rate will return in the forthcoming decades for some time to a hyperbolic trajectory – this time with the singularity parameter being equal to 2106, which implies that in the late 21st and the early 22nd century the global macrotechnological growth rate will experience one more decline, and there are some grounds (see the next section of this paper) to expect that this decline will be much more pronounced than the one of the recent decades.

5. Global Ageing as a Factor Influencing the Technological Growth Rate

5.1. Ageing and Technological Progress: A Positive Feedback

We believe that global ageing is one of the most important factors in the coming decades. In the previous articles we have already shown how the process of global ageing can develop up to the 2070s and influence technological progress (Grinin L., Grinin A., and Korotayev 2017a; Grinin L., and Grinin A. 2015a; Grinin and Korotayev 2015b, 2015c, 2015d, 2016; Grinin L. and Grinin A. 2015c, 2015d, 2017). The present article is a continuation of our research regarding the correlation between global ageing and technological development, which allows to significantly expand the forecast horizon and obtain new results. This valuable result is that global ageing can cause a new technological acceleration with a change in direction, and then by the end of the present century – the beginning of the next century – on the contrary, it can be slowed down also with a change in direction.

In this section, we will look at how and why global ageing in the coming decades could become one of the most important drivers of a technological breakthrough until the 2070–2080s, and we will discuss why later global ageing will become an obstacle to technological progress.

As we expect, a new technological breakthrough will begin around the 2030s, starting in new branches of medicine and related areas: bio- and nanotechnologies, additive and cognitive technologies, and some others. It will also mark the beginning of the final phase of the Cybernetic Revolution. As we pointed out before (Grinin L., Grinin A., and Korotayev 2017a) for the start of such breakthrough in the 2030s in the sphere of new medicine, the world will have the following prerequisites: the explosive growth of the elderly population; growing economy's need for labor resources and the state's interest in increasing the working capacity of older people, as well as a growing number of well-to-do and educated people concerned about their health. *Huge financial resources will also be accumulated for technological breakthrough, namely: pension funds, which will increase at a rapid pace; government deductions for health and social needs; increased spending on health care by an ageing population and a growing world middle class. All these resources are able to provide high investment attractiveness of various venture capital projects and, in the long-term, a very wide demand for innovative medical and other technologies.*

We also expect that in the process of the Cybernetic revolution there will be formed the MANBRIC-complex, where new medical technologies will play an integrating role. This will have a double effect: on the one hand, it will affect the growth of life expectancy, its physiological quality and increase in the age limit of physical activity. On the other hand, the problem of the explosive growth of the number of older people will become more acute, especially because of pension costs and labor shortages.

As a result, medical technologies will rapidly develop under the influence of an ageing population (Phillips 2011), and this will expand the search for opportunities to create 'smart', self-regulating systems, including robots, which can largely replace human labor, especially in the service sector (Frey and Osborne 2017) including complex services (*e.g.,* in the field of elderly care, education, medicine, *etc.*) (DeCanio 2016).

Thus, until the last third of our century, the ageing of the population will not impede technological and other development. On the contrary, the process of global ageing itself will be the driving force of change, reform and acceleration of technological innovation.

5.2. Global Ageing and Technological Progress in the Last Third of the 21st Century and the Beginning of the 22nd Century: Possible Negative Feedback

The link between global ageing and technological progress is non-linear. At some point, the positive feedback that we mentioned above is likely to be replaced by a negative feedback. Why? It is important to note that older people are more conservative; and this is not just a popular belief, but a fact confirmed by rigorous scientific research (see, *e.g.*, Grinin L., and Grinin A., 2017; Korotayev, Zinkina *et al*. 2017; Korotayev, Shulgin *et al.* 2018; see also Tsirel 2008).

Of course, we do not claim that older people are absolutely conservative, but only that in general they have less needs and a desire for innovations than young people. In such fields as medicine and pharmaceuticals, older people tend to be more innovative than young people. There are studies, the authors of which claim that the change for cohort-in-later-stages (aged 60 and older) is going to be greater than that for cohort-in-earlier-stages (Danigelis, Hardy, and Cutler 2007). However, this may be true only for some narrow areas. Our study focuses on wider aspects: the desire for technological innovation and consumption of new goods, the adaptability to them. In terms of adaptation to technological progress, in the pursuit of changes and the rate of acquisition of new skills, older people are much inferior to younger ones.

In any case the psychology of older people is very different from the psychology of younger ones that can be implemented in different issues.[14] In general, acquiring new skills is more difficult for older people than for young people (*e.g.,* Zemnyakova and Pomuran 2014; about the difficulties of the elderly people in adaptation to the Internet see Neskromnykh and Mamadaliev 2017). In addition, older people are less productive than young people (*e.g.,* people aged 40–65 compared to the workers aged 20–40 [Goldstone 2015], whose productivity tends to increase rapidly with increasing experience and education (Lee and Mason 2011).[15] Not to mention the people older than 65.

As for consumerism, older people who have already acquired, experienced and seen a lot, have largely lost their desire to pursue new things and have become less active than the younger ones. The situation in the Japanese economy, where the proportion of the elderly is growing, and the proportion of the young people is decreasing, confirms this fact. This demographic structure of the population cannot contribute to more or less noticeable economic growth. The Jap-

[14] A good example is the study of foreign languages. It is well known that children and the teenagers learn foreign languages more easily than elderly people.

[15] According to other researches, labor productivity peaks between the ages of 35 and 54 (Park and Shin 2015: 109).

anese economy suffers from a weak period of GDP growth with two and a half decades of deflation due to an ageing population that does not want to spend too much money and prefers to save instead. No wonder Japan's mood is rather depressed (Coleman and Rowthorn 2015: 31; Ogawa, Kondo, and Matsukura 2005; Coulmas 2007; Grinin and Korotayev 2014b, 2017, 2018).

In addition to slowing consumption in an older society, the most important driver of development, namely the need for career growth, well-being and success, will fade away. With a decrease in the number of children, investments in the younger generation and the need for their provision will begin to weaken, which is another important factor for development.

UN Population Division forecasts rather confidently that by the end of this century no significant population growth will be observed in the overwhelming majority of the countries of the world, and many of them will experience population decline (UN Population Division 2019), whereas throughout the human history the population growth has been the most important development driver (Kuznets 1960; Boserup 1965; Grossman and Helpman 1991; Aghion and Howitt 1992, 1998; Simon 1977, 1981, 2000; Komlos and Nefedov 2002; Jones 1995, 2003, 2005; Korotayev, Malkov, and Khaltourina 2006a, 2006b; Khaltourina *et al.* 2006; Kapitza 1996, 2003, 2006, 2010; Grinin L., and Grinin A., 2015c, 2016, 2017; Grinin *et al.* 2014, 2015; Korotayev and Markov 2015; Korotayev 2005, 2007a, 2012, 2013, 2018; Dolgonosov 2016; Fomin 2020).

Therefore, it is likely that in 50–70 years, that is, by the end of the 21st century, the situation will change significantly around the world, even in those societies where large 'youth bulges' and high birth rates are observed, *i.e.*, in most or in all Tropical African countries (Korotayev and Zinkina 2014, 2015; Zinkina and Korotayev 2014a, 2014b; Grinin L., and Grinin A. 2015c, 2017).

In the long term, the number of elderly people worldwide will increase. Thus, in the next few decades, the behavior of societies will be different (see Grinin L., Grinin A., and Korotayev 2017a). This will probably coincide with the period of transition to a certain societal stability after the end of the Cybernetic revolution. However, of course, other scenarios are also possible, for example in case of climate deterioration, some societal degradation may as well occur. *Thus, it is possible that the ageing of society with the end of global population growth and improved social planning capabilities, will contribute to the transition of global society to a more comfortable and slow development (the so-called sustainable development, which is much talked about) by the end of this century or at the beginning of the 22nd century.*

And all this will affect scientific and technological progress and its slowdown.

Conclusion, Transition to a New Economic Model

The abovementioned conservatism may lead not only to a slowdown in development but also to a transition to another economic system. The current model is associated with an increasing consumption. The model 'Consume today more than yesterday, and tomorrow more than today' appears to be rather absurd. Furthermore, sometimes the pursuit of sustainable GDP growth seems absurd as well. However, this model works and will work for decades, especially for poor countries whose populations are not satisfied with their level of consumption. Thus, ageing can change people's needs, especially in conditions of stabilization of the population or its reduction. As a result, under the influence of all above-mentioned future changes, the model measuring economic growth in GDP should be replaced (Coleman and Rowthorn 2015: 37). The modern consumption model will also change.

The transformation of the modern consumption economic model will be a complex process that can change many important aspects of our life. Above, we mentioned Japan as an example of an ageing society. It also provides an example of development without GDP growth along with scientific and technological development. 'The Japanese' disease has recently spread to European countries, partly also due to the ageing population (there are other reasons as well, although we do not address them in this article; for more details see Grinin and Korotayev 2014b, 2017, 2018).

But overall, the Cybernetic revolution and ageing should eventually move society towards a new economic model without an endless increase in consumption. In such case, the growth model in the economy should differ from today's one, it is likely to include some parameters of quality and longevity. Accordingly, business models may change, although it is not very clear how this will happen.

Concluding the article, one should note that there is still an upward trend in technological growth at a macro scale, albeit with fluctuations. However, as we have seen, the upcoming technological growth will not be infinite. In the article, we have demonstrated a scenario of how, when, and why this will change. First, the slowdown in technological growth in recent decades, beginning in the 1970s, can be explained as a general fluctuation of technological growth. We consider this slowdown as a necessity for further rapid growth. Secondly, our analysis shows that there is a number of reasons to expect that in the forthcoming decades global technological growth rate will return for some time to a hyperbolic trajectory when the final phase of the Cybernetic revolution begins. Thirdly, this acceleration will continue up to the late 21st century. Fourthly, at the end of the 21st century the technological growth will gradually slow down and will reach the singularity point in 2106. As we have seen, global population ageing will play a key role here. After the singularity the rate of technological progress will slow down compared to the previous epoch. Fifth, it is difficult to predict any subsequent acceleration in the 22nd century (at least in its first half). And, probably, the most important point is that the pattern of scientific and technological development itself will change dramatically.

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