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IN MEMORY OF VITALY LAZAREVICH GINZBURG

On the theory of global population growth

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Contents

Abstract. **Ours is an epoch of global demographic revolution, a time of a rapid transition from explosive population growth to a low reproduction level. This, possibly the most momentous change ever witnessed by humankind has, first and foremost, important implications for the dynamics of population. But it also affects billions of people in all aspects of their lives, and it is for this reason that demographic processes have grown into a vast problem, both globally and in Russia. Their fundamental understanding will to a large extent impact the present, the short-term future following the current critical epoch, the stable and uniform global development and its priorities, and indeed global security. Quantitative treatment of historical processes is reached using the phenomenological theory of mankind's population growth. This theory relies on the concepts and methods of physics and its conclusions should take into account the ideas of economics and genetics.**

1. Introduction

The main purpose of the present study is to explain why the theory of world population growth published earlier [1–4] proved to be so rich in results. This conclusion is based to a great extent on the approach whereby the entire population of the globe over an immense timescale is treated as a **unified system**. To many, however, a regional approach and the socio-economic analysis are more trusted and understandable than the physicist's phenomenological theories and the mathematician's still more abstract models. It is regrettable that the approach developed below is so difficult to accept for traditional demographers, even though the holistic integrity of the demographic system of humankind is incontestable.

In fact, demography — for which numbers represent universal characteristics of the population — is the field where the methods of physics and mathematics are natural tools for the quantitative study of population growth and evolution. At the same time, these tasks constitute one of the more important problems in science for a physicist. This is the reason why the author addresses physicists, historians, demographers, and economists with a request to show mutual understanding and cooperation in this new field of interdisciplinary research. This social contract stems from the critical state of the global community in the epoch of a demographic revolution, the time that requires new understanding of the entire history of humankind. It is not accidental that all major historians, such as Fernand Braudel [13], Karl Jaspers, Immanuel Wallerstein, N I Konrad, and I M D'yakonov insisted that the only true history of humankind is **metahistory — the history of mankind as a whole** — and that this is the fundamental issue in the social sciences. This formulation of the problem stimulated the author of the present article to extend the application of the quantitative theory of population growth to cover the entire existence of humans on the planet, beginning from the epoch of anthropogenesis.

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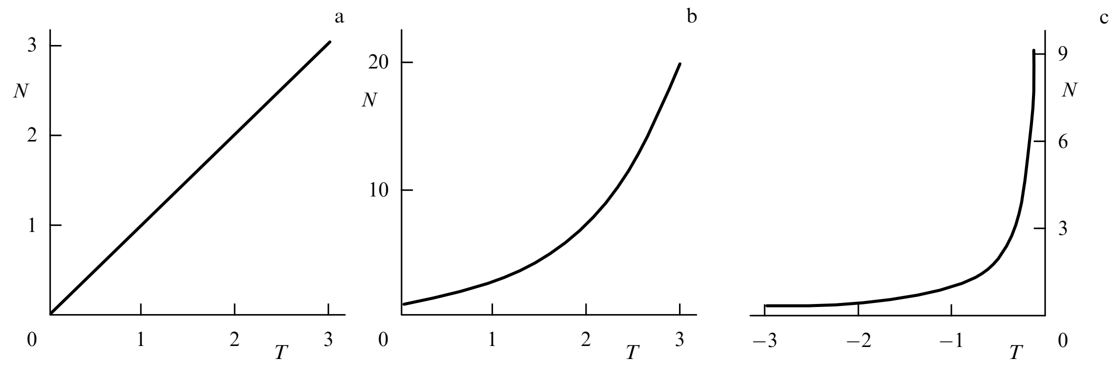
2. Growth of world population from the earliest times to the foreseeable future

To describe population growth one usually turns to models that show population size as a function of time. Linear growth, in which population increases in direct proportion to time, appears to be the simplest case (see Fig. 1a). What is taken into account are the initial conditions for time and for population itself; here, for simplicity, they are set to zero. The next case illustrated here is that of exponential growth, or the law of compound interest, when growth is described by the



$$\frac{dN}{dT} = A\,, \quad N = AT \qquad \frac{dN}{dT} = \frac{N}{\tau}, \quad N = N_0 \exp\frac{T}{\tau} \qquad \frac{dN}{dT} = \frac{N^2}{C} = \frac{C}{(T_1 - T)^2}, \quad N = \frac{C}{T_1 - T}$$

Figure 1. Models of linear (a), exponential (b), and hyperbolic (c) growth.

exponential curve given in Fig. 1b, with time constant τ. The time of doubling is correspondingly $\tau \ln 2 \approx 0.7\tau$, and the growth rate increases in proportion to population size. This process is additive, as is linear growth, and reproduction in this mode proceeds for each individual in population independently of others.

In the case of Earth's population, the case of maximum interest is that of growth proportional to population size squared (shown in Fig. 1c). This is essentially the nonlinear law of growth of a group of people which assumes interrelations — cooperation — between individuals within the group. Obviously, this pattern of population growth is only applicable if population is treated as an integrated body. The most important feature is that this law of growth is immediately detected if we consider the growth of the entire population of our planet, assumed to form a self-sufficient and integrated object. The recognition of this fact forms the cornerstone of the theory of growth that we present below consistently and in detail.

The interpretation of the growth of world population system is thus based on the concept of universal interaction, which follows from analyzing the population growth pattern and arises in mankind evolving as a unified population. The collective interaction results in hyperbolic growth in which the world population tends to infinity at a finite instant of time around the year 2000. This mechanism serves to transmit the most diverse culturally and technologically significant information, thereby defining the evolution of the system as a whole. The interaction is a product of consciousness, memory, and language as factors of social heritage, which manifest themselves via social consciousness and culture, skills and beliefs, and nowadays via science as well. In doing so, dissemination of information proceeds both horizontally in space and vertically in time. After the initial singularity, linear growth is replaced with quadratic growth [19]. In other words, the theory rests on four assumptions:

(1) The entire world population is regarded as a unified strongly coupled evolving system.

(2) Its growth rate is proportional to the world population number squared. This law is a product of a universal interaction which, being an internal process, is independent of external resources.

(3) The interaction is based on the proliferation and dissemination of information of various types.

(4) A group of people consisting of about 60,000 persons is defined as coherent and self-sufficient population.

The task of the theory consists not so much in a description of known facts as in a unification of our notions using our understanding of the relationship between growth and evolution. These notions were introduced as independent elements into models and only in a consistent nonlinear theory can we achieve an interdependent and noncontradictory description of the whole. As these statements are not self-evident, we need to provide rationale that these are properties inherent in the physics of an evolving system, and we should also be able to explain this in terms that are comprehensible to a historian and demographer or economist.

In a phenomenological theory we shall turn to a generalized description of population growth, in contrast to models where a number of growth factors are summed up. These introductory remarks will be clarified by considering the data on the growth of Earth's population during the last 4000 years

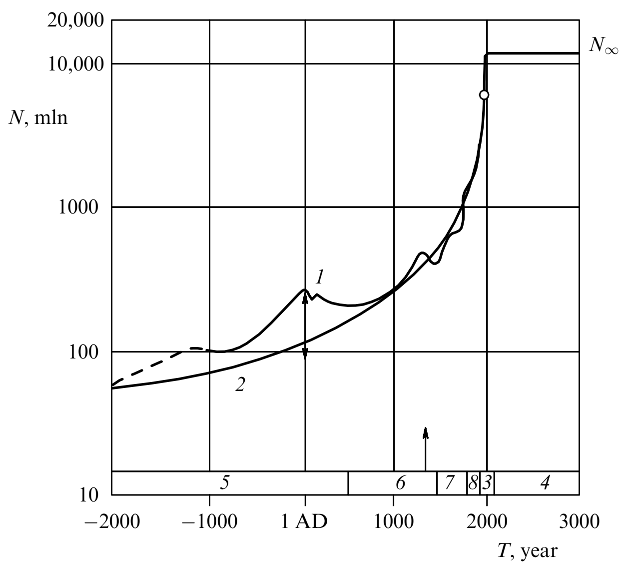


Figure 2. World population from the year 2000 BC until 3000 AD. *1* — world population from year −2000 until the current era (CE), *2* — blow-up model of population growth, *3* — demographic transition, *4* — stabilized population, *5* — ancient world, *6* — Middle Ages, *7* — modern history, and *8* — contemporary history, ↑ — pandemic plague 1348, ↕ — data spread, ○ — $N_1 = 5.7 \times 10^9$ persons for $T_1 = 1995$ AD. On the time scale of this plot the time of the onset of anthropogenesis (5 mln years ago) lies at a point one hundred meters to the left! All other plots are drawn on a larger scale and act as a "time lens" which shows many details of the process of growth.

(Fig. 2). A plot showing population size N on a logarithmic scale as a function of time on a linear scale would have exponential growth shown by a straight line, but this is not what we observe. The theory has no need of birth rate and death rate parameters or of characteristics of migration or resources: this is another, essential difference between the approaches used in models and in the phenomenological theory. In this way we turn directly to observable growth data and to values that characterize the hyperbolic growth of humankind since the emergence of the initial population of consciousness-endowed humans. To describe the growth in the system and to identify self-similar processes, we turn to asymptotic methods (see Ref. [20]).

The suggested treatment, as any other theory, describes our world only approximately, and the demographic data as such are disparate and approximately known. Nevertheless, since the population of Earth has grown a hundred thousand-fold since the arrival of the genus *Homo*, inaccuracy of data does not affect the final averaged result too much. In turn, it is natural to present the hyperbolic growth as logarithms of time and size of the population of the world and mankind as a whole. Table 1 gives data for N, following the latest reports by demographers and anthropologists [12], and the results of calculating N_m starting with the anthropogenesis epoch. This is when the genus *Homo* emerged, as we now understand, and its numbers began to grow.

Several authors (Förster, Hörner, I S Shklovskii [5]) noticed that the growth was hyperbolic. The first was perhaps the Scottish epidemiologist Anderson Gray McKendrick (1876–1943), as the American demographer Nathan Keyfitz pointed out for me:

$$N = \frac{C}{T_1 - T} = \frac{200}{2025 - T} \times 10^9 \,. \qquad (1)$$

The constant $C = 162$ billion persons year gives the population size of the world one year before N becomes

Table 1. World population growth (in millions of persons).

Year	N	N_m	Year	N	N_m
-4.4×10^6	(0)	1×10^{-6}	1960	3039	3245
-1.6×10^6	0.1	0.1	1965	3345	3497
−35,000	1 – 5	2	1970	3707	3778
−15,000	3 – 10	8	1975	4086	4089
−7000	10 – 15	16	1980	4454	4430
−2000	47	42	1985	4851	4801
0	100 – 230	86	1990	5277	5198
1000	275 – 345	173	**1995**	**5682**	**5613**
1500	440 – 540	345	2000	6073	6038
1650	465 – 550	492	2005	6453	6463
1750	735 – 805	685	2010	6832	6878
1800	835 – 907	851	2025	7896	7987
1850	1090 – 1110	1120	2050	9298	9259
1900	1608 – 1710	1625	2075	9879	9999
1920	1811	1970	2100	10,400	10,451
1930	2020	2196	2125	10,700	10,745
1940	2295	2474	2150	10,800	10,956
1950	2556	2817	2200	11,000	11,225
1955	2780	3019	2500	—	11,364

infinite. This constant is dictated by the length of the year, not by human nature. Hence, the characteristic time $\tau = 45$ years, equal to the half-width of the demographic transition time, appears as the inherent scale of time and human life. For all subsequent calculations it will be appropriate to introduce, instead of the dimensional constant C, another constant $K = 60{,}000$ as a large parameter of the theory. Considering that $C = \tau K^2$, we obtain two quantities K of identical magnitude but of different dimensions — one with the dimension of the number of persons, and another dimensionless, giving the ratio of times:

$$K = \sqrt{\frac{C}{\tau}} = 60{,}000 \,. \qquad (2)$$

It is K that stands for both the interaction itself and the behavior of the system, and represents all specific results of the theory which characterize the evolution of humankind. The quantity $\sim K$ determines the initial size of the population which possesses, after a very long epoch of anthropogenesis, a structural and functional self-sufficiency. This also defines the instant of time of the first demographic transition when the initial linear growth is replaced by a quadratic stage. The numbers of $K \sim 10^5$ are typical of the population of mono-towns, such as a university town or a district in a megapolis. For instance, Moscow had its population of about 10 million persons split into a hundred administrative boroughs. Note that a population whose size is less than 50,000 persons is classified as a small group of people. Isolates that have been long separated from the rest of the main mass of mankind invariably lag behind in their social and cultural evolution.

Hyperbolic population growth lasts for about one and a half million years and covers five orders of magnitude, $\sim 10^5$, from the end of the epoch of anthropogenesis to the current era. With growth rate proportional to N^2, the time from the end of each cycle to our days is approximately equal to one half of the duration of the cycle. Thus, the lower Paleolithic Era lasted for a million years and ended 500,000 years ago. The Middle Ages lasted for a thousand years and ended 500 years ago, as historic processes rolled on a thousand times more rapidly. This acceleration continued to the current epoch and ended with a transition to a period when the characteristic time of changes becomes comparable with human lifespan τ.

3. The global demographic transition

The demographic transition was discovered by the French demographer Adolphe Landry for the French population, and he correctly described this phenomenon as a revolution [10]. Moreover, the global demographic revolution is undoubtedly **the most significant event in the entire history of humankind**. During this revolution, the paradigm of global development changes abruptly, as in a powerful shock wave, from very rapid growth in the demographic explosion to the consequent stabilization of the world population number.

The demographic transition involves the entire population of our planet and lasts for only about a hundred years, regardless of all the differences in the previous histories, ways of life, and economics of different countries. The synchronous behavior and narrowing of the transition period clearly point to the interaction between populations of all countries in the **blow-up mode**, when globalization reveals the behavior of the entire system [7, 8]. This is a nonlinear process caused by the divergence of growth because it is accelerated when approaching the fatal date of the singularity, and it results in dominance of the hyperbolic growth, while all other factors, including resources, practically leave the accelerated growth of population unaffected. This leads to an important conclusion that growth is dominated by N, and hence shows no explicit dependence on resources. By the moment of demographic transition circa 1995, the world population suddenly stops its rush towards the infinity of the demographic explosion, ceases growing, and then moves to a stable plateau, tending asymptotically as $N_\infty - N \approx 1/T$ to a constant limit $N_\infty = \pi K^2 = 11.4$ billion people (ppl) (Fig. 2).

Figure 2 illustrates that the demographic transition can be represented in the form of a **phase transition**, as this image helps to better understand the essential features of the transformation that fate makes us go through when the explosive growth of the world population rapidly slows down. If before and after the phase transition the growth is described asymptotically by a hyperbolic curve, then during this transition the growth rate needs regularization as a divergence due to 'small denominators', by means of the introduction of time τ:

$$\frac{dN}{dT} = \frac{C}{(T_1 - T)^2 + \tau^2}, \tag{3}$$

which limits growth close to the transition point as $T \to T_1$. Integration of this equation yields

$$N = \frac{C}{\tau} \cot^{-1}\left(\frac{T_1 - T}{\tau}\right) = K^2 \cot^{-1} t. \tag{4}$$

We see that the population transition is described by the function $\cot^{-1} t$, where the time $t = (T_1 - T)/\tau$ is measured in units of $\tau = 45$ years. As a result, the number of people on the globe equals $N_1 = (\pi/2) K^2 = 5700$ million ppl at the moment $T_1 = 1995$ AD when the rate of growth of the world population reaches a maximum:

$$\left(\frac{dN}{dT}\right)_1 = \frac{K^2}{\tau} = 80 \text{ mln ppl y}^{-1}. \tag{5}$$

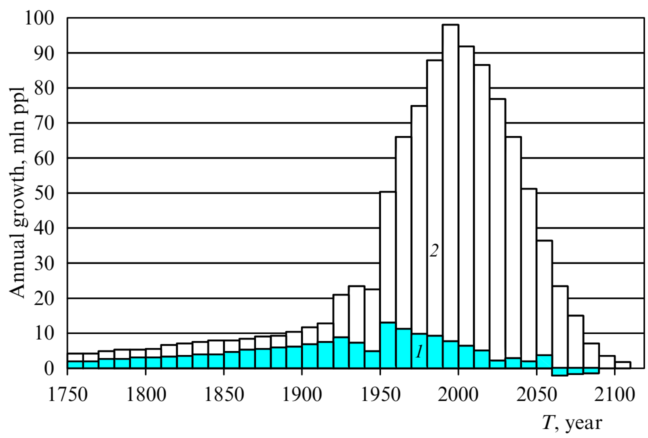


Figure 3. Global demographic transition of 1750–2100 (UN data). Annual growth was calculated by averaging over a decade. The figure shows decreases in growth rate in response to world wars and the demographic echo of the war at the end of the 21st century. *1* — developed countries, and *2* — developing countries.

Compare Fig. 3, where the population increment is 87 mln ppl y^{-1} and, as follows from the data of Table 1, $[N(2000) - N(1990)]/10 = 80$ mln ppl y^{-1}.

Accordingly, we arrive at the following 'age of mankind' by estimating the time when anthropogenesis began:

$$T_0 = \frac{\pi}{2} K\tau = 4.2 \text{ million years ago}, \tag{6}$$

which is completely consistent with anthropologic data. Integrating population growth from T_0 to T_1, we obtain the estimate

$$P_{0.1} = \frac{45}{20} K^2 \ln K = 96 \text{ billion ppl} \tag{7}$$

for the total number of people who ever lived. The factor 45/20 emerged because the characteristic time for one generation in the work of other authors was assumed to be 20 years, which leads to the estimate $P_{0,1} = 106$ bln ppl [9]. Expression (7) for $P_{0,1}$ indicates that the entire evolution of human population can be described as a sequence of exponentially shortening **civilization cycles** as we approach the instant of transition. The number of people who lived during each cycle was $\Delta P = 2.25 K^2 = 8$ billion ppl, which constitutes the dynamic invariant of hyperbolic growth.

The chronology of the Stone Age and of the subsequent epoch obtained in this manner agrees satisfactorily with the data of history and anthropology. Notice that these epochs were distinguished by technological and cultural markers, not by changes in the population size which stem from the evolution of culture. The Neolithic Period is the transition from scattered population to its concentration in villages and towns, and is accompanied with progress in agriculture and trade between rural and urban areas.

The Neolithic Period, which began 10 thousand years ago and sits right at the midpoint of the history of mankind, is shown in Table 2 on a logarithmic time scale. It pertains to history, not to the Stone Age. Traditionally for anthropology, the Stone Age chronology is plotted on a logarithmic scale, in accordance with the theory, as it would be difficult to adequately represent ten thousand years of the Neolithic Period on the same page as millions of years of the Paleolithic Period.

This was not done for the period of history because it was not clear which datum to choose to measure the remoteness of the past. The same theory indicates that $T_1 = 1995$ AD, or a rounded number 2000 can be set as the reference point (zero). Then the remoteness reckoned from the borderline of ages determines the relative rate of instantaneous exponential growth. For instance, in 1900 mankind was growing on average by 1% per year, and at the onset of the current epoch, by 0.05% per year. The range covered by the asymptotic law of hyperbolic growth is implied by the large parameter K and its logarithm $1 + \ln K = 12.00$ points to the number of cycles of such a self-similar growth process. In the end, this exponential periodization leads to a sequence of phase transitions.

The notion important for history is that of duration, which arises as a measure of the inner rates of social evolution, independent of the outer passage of time [13]. Time being a continuous variable and the number of people a discrete one, this finite countable set results in a chaos of fluctuations and short-period historic processes 'in the small picture', while 'in the large picture' it gives a stable deterministic evolution. As we approach the demographic

Table 2. Growth and development of humankind on a logarithmic scale.

Epoch	Period	Date, years	Number of people	Cultural cycle	ΔT, y	History, culture, technology
C		2150	10×10^9	Stabilized world population		Moving to the limit 11×10^9 ppl
		2040	9×10^9		125	Age distribution change — ageing
	T_1	1995	6×10^9	World demographic transition	45	Globalization Urbanization
B	11	1950	3×10^9		45	Computers. Internet. Nuclear energy
	10	1840	1×10^9	Contemporary history	110	World wars Electrification and radio communication
	9	1500		Modern history	340	Industrial revolution Book printing
	8	500 CE	10^8	Middle Ages	1000	Geographical discoveries The fall of Rome, Muhammad
	7	2000 BC		Ancient world	2500	Christ, 'Axial time'. Greek civilization India, China, Buddha and Confucius
	6	9000	10^7	**Neolithic**	7000	Mesopotamia, Egypt. Writing, cities, Bronze Age Domestication of cattle, agriculture
	5	29000		Mesolithic	20,000	Ceramics Microliths
	4	80,000	10^6	Moustier	51,000	Populating America Languages, shamanism
	3	0.22 mln		Acheulean	140,000	*Homo Sapiens*, Speech, mastering fire
	2	0.60 mln		Chelles	380,000	Populating Europe and Asia Paleolithic flint tools
	1	1.6 mln	10^5	Olduvai	1,000,000	Pebble Culture, chopper *Homo Habilis*
A	T_0	4–5 mln	(1)	Anthropogenesis, Emergence of gene HAR1 F	2,800,000	Origin of socialization Development of hominids with a great potential of brain and consciousness

transition, the inner time scale takes a value on the order of the characteristic inherent lifespan of a human being and cannot be compressed anymore. Consequently, the very inner characteristic time of evolution in this essentially nonlinear theory depends on population as it does on an **order parameter**.

The problem of time in history was analyzed by I M Savel'eva and A V Poletaev, who in their review monograph [11] singled out Time-1 as Newton's outer absolute time, and Time-2 as inner system's time of duration (*longue durée*), defined as a logarithm of Time-1. The notion of inherent growth time and irreversibility of evolution, i.e., the emergence of the 'arrow of time' in the evolution of complex systems, has been analyzed by I Prigogine and I Stengers [6]. This understanding of the duration of evolution resembles the time transformation in general relativity where the evolution of a gravitating system dictates the flow of time. If the Universe in its evolution expands from the initial singularity, then self-organization forces humankind to move from this singularity to synchronous and global demographic transition by way of explosive self-similar growth.

4. Global interaction in a demographic system

The basic differential equation is autonomous and connects growth rate to development:

$$\frac{dN}{dt} = \frac{N^2}{K^2} \,. \tag{8}$$

In other words, growth is a function of the instantaneous value of N and is proportional to the world population **squared** N^2 as a measure of network complexity. **Nonlinear dependence** of growth on N makes it impossible to apply equation (8) to an individual country, but the development of each country should be evaluated against the background of the aggregate growth. It should be noted that Eqn (8) does not cover migration, since the entire world population is confined to Earth and displacements of people leave the total number of people invariant. [1]

[1] It is interesting to remark that with the current energy resources available to humankind (about 500×10^{18} J per year) this energy would, in principle, be sufficient for launching every one of us on the planet into cosmic space.

Therefore, the quadratic interaction is **nonlocal** in the first approximation, since it covers the population of the planet in its totality. An analogy with the van der Waals interaction is useful for understanding the nature of this nonlinear interaction. In the physics of nonideal gases this quadratic law does not stem from specific interactions between particles, but emerges as a result of the collective interaction proportional to the square of the gas density.

It would seem that the dependence on the instantaneous value of N makes memory of the past impossible. However, as pointed out above, we are dealing here with quantities averaged over time, and averaging time **introduces memory of the past**, so that we need to treat N and T as their effective values. This means that averaging occurs over a time on the order of the remoteness, and the relative constancy of averaging manifests itself in the self-similarity of growth.

And finally, an important conclusion is that the above treatment ignores the factor of resources — be they space, mineral deposits, or food resources. This approach found its expression in the **principle of demographic imperative**, stating that development on the whole is dictated by processes internal to humankind, so in the framework of advanced theory it is not directly connected to resources [14, 15]. This paradoxical statement contradicts both the Malthusian Principle of Population and models of 'growth limits' of the Club of Rome and other groups in which the evolution of humankind is limited by resources. Population growth is independent of resources by virtue of the fact that resources only support growth but do not determine what it should be.

For example, during the Paleolithic Period there were sufficient resources and many children, but growth was very slow since it was dominated by the internal informational factor proportional to the square of the world population, i.e., by the total number of binary links serving as a measure of network complexity or, in other words, as the interaction field. The driving force of growth should be sought in the fact that it was always the internal mechanism of quadratic growth that dictated the growth rate which determined the evolutionary speed on **average**. This self-similar, **stable-in-the-large** evolution continues despite wars or epidemics, failed harvests or famines — these were tragic episodes, of course, but nonetheless they managed local history. For example, total losses in the course of World Wars I and II from 1914 till 1945 came to 250 million, or 8% of the world population (Fig. 4). Nevertheless, after the world wars the global population returned to the previous, nonperturbed trajectory and then continued this course, up to the onset of the demographic revolution. During this time, the global population increased almost twofold — from 1.7 billion to 3 billion, and the presence of demographic cycles themselves points to the stability of global growth. By Lyapunov's criterion, the growth of a demographic system after the transition is asymptotically stable. If the hyperbolic growth unconstrained by the transition could continue as before, the population of Earth would reach 13 billion by 2010 — twice as much as the current 6.8 billion. This should give a good idea of the scale of the phenomena involved and driving forces.

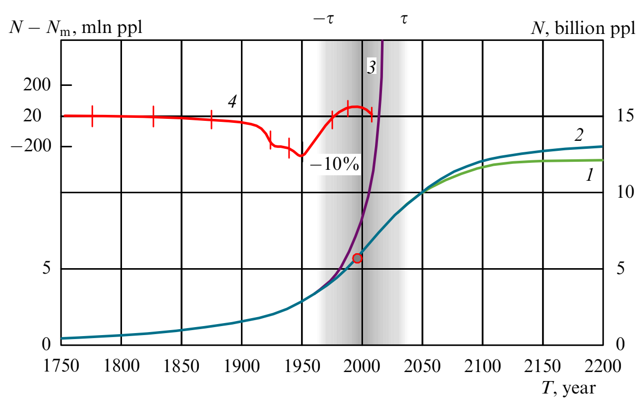


Figure 4. World population growth in the course of the demographic revolution of 1750–2200: *1* – IIASA forecast, *2* – model, *3* — explosive growth to infinity (blow-up mode), *4* — difference between the calculated result and the actual world population, ×5, revealing total losses in the 20th century world wars, ○ — $T_1 = 1995$ AD, and $N_1 = 5.7$ billion ppl. The duration of the global demographic transition equals $2\tau = 90$ years.

Let us turn, however, to the dawn of humankind some million and a half years ago. The initial size of the population came to about 10^5, i.e., it was the same by order of magnitude as such species as wolves and apes, which are similar to humans in food patterns and reproduction. Considered individually, these animals occupy their ecological niches in the biosphere and slowly evolve, existing in dynamic equilibrium with other species and the environment. It was at this very epoch that anthropogenesis triggered the development of consciousness, which led to language and speech, and social consciousness; humans mastered fire and started to proliferate and migrate to every habitable location on Earth. This qualitative leap in evolution was accompanied by profound changes in brain organization, so humankind started to grow numerically without having to compete against other species.

Perhaps the main problem for life sciences in evaluating the role of the new mechanism of heredity based on conveying information through culture and its carriers is to understand what precisely happened at that moment. This mechanism of **epigenetic** social heredity differs from genetic heredity, in which the carriers are genes. Selection works in both of these mechanisms of evolution and includes, in particular, selection of social structures, while intellect and epigenetic social heredity resulted in explosive growth of the number of people on our planet.

5. The foreseeable future

The results obtained make it possible to address the predictions of the evolution of humankind, which will set in after the completion of the global demographic revolution. The revolution is to end by the middle of the current century, when the world population reaches the level of 10–11 billion persons and growth will be essentially over. This is implied both by theoretical predictions and by demographic forecasts (Fig. 4). Important changes will happen in our current world in the patterns of employment. At the beginning of the 20th century almost one-half of the work people in the USA was engaged in agriculture, but as a result of enormous improvements in labor productivity, by the end of the century this fraction dropped to 1–2%, despite the fact that agriculture is subsidized by the State and half of the produce is exported.

Increased labor productivity and export of technologies led to a drop in the size of the industrial workforce. For instance, it now takes 10 to 20 working hours to produce one medium class car. Up to 80% of the workforce in developed countries is now occupied in the 'soft' sector of the economy –

in education and management, science and innovation, health services and culture, tourism and entertainment industries.

On the other hand, the age distribution of the population indicates that humankind is to undergo ageing in the next fifty years. These data were also obtained by demographic methods, since the theory gives only averaged data for the total population of the world and does not operate with age distributions of population cohorts. The above data lead to a conclusion that the foreseeable future will bring changes to both occupations and the age composition of the population (Figs 5 and 6). These two factors should lead to a change in retirement age and to redistribution of occupation data over ages of the population as a result of the demographic transition.

The advanced theory addresses the effective characteristics of the demographic system. However, distributions better describe its characteristics. The population of cities, towns, and villages of the world is ranked by the hyperbolic distribution, which is an indication of their belonging to a unified global fractal system [4]. However, in economics income distributions, described by the Pareto power law, are typically shown only for individual countries. It would therefore be of interest to construct a distribution that would cover the entire population of Earth, including homeless, clochards, oligarchs, and billionaires. Consequently, the passage from effective quantities to their distributions would lead to the creation of a **statistical** theory of growth. It is essential that these distributions emerge as power law expressions, thus indicating that the demographic system departs from equilibrium state. As the demographic revolution unfolds further, the degree of departure from equilibrium economy only enhances both globally and in individual countries, leading to social tensions and phenomena generated by the economic crisis.

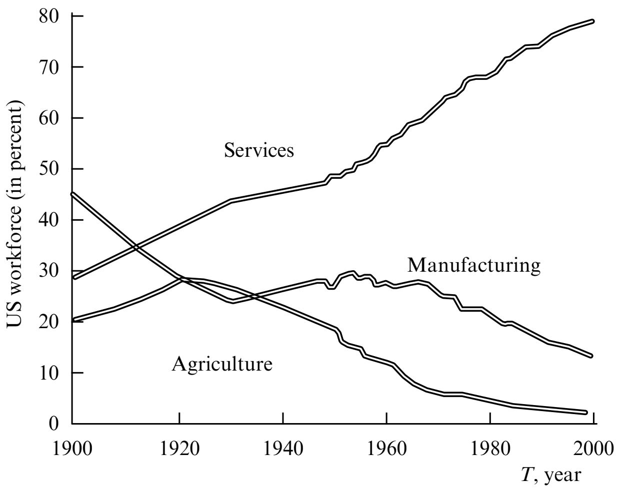


Figure 5. Distribution of workforce over sectors of American economy in the 20th century.

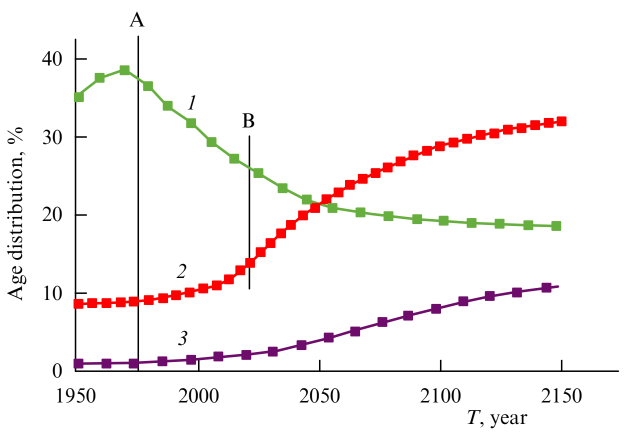


Figure 6. Ageing of the world population during the demographic revolution of 1950–2150: *1* — age group below 14 years of age, *2* — older than 65 years, and *3* — older than 80 years. (UN data.)

This source of inequality can in some cases be reduced by the intervention of the State, but under the uncontrollable free market economy the inequality and chaos in society grow all the same. After the transition, globalization processes in the world population will continue, and will perhaps result in the onset of self-organized, synchronous global socio-economic cycles with a period of $\sim \tau$.

Neoclassical economics according to Leon Walras begins with the notion of equilibrium in a slowly evolving system with reversible economic processes. Thermodynamics, which became the archetypical theory for economics, assumes the existence of equilibrium conditions in the system. However, these concepts of quasiequilibrium in the economic system contradict conclusions on enhancing nonequilibrium in an evolving demographic system of the world population. A resolution of this paradox appears to be an important problem for econophysics: how to reconcile the postulates on local equilibrium in economics and the intrinsically nonequilibrium evolution of the world population as a whole; in the latter case, the limiting factor is not the insufficiency of resources but the nonuniformity of the distribution of evolution results. The problem due to limitation by insufficient resources may only arise in the future, when developing countries succeed in increasing their labor productivity. On the other hand, the conclusions of the growth theory should be compared with the current understanding of the paleogenetics of the genus *Homo*.

The independence of growth from resources is a reminder of a symptomatic remark of the American historian Francis Fukuyama: "Failure to understand that the roots of economic behavior lie in the realm of consciousness and culture leads to the common mistake of attributing material causes to phenomena that are essentially ideal in nature." [18]. Our social evolution is determined precisely by these factors, which are passed on through the information field.

There is no doubt that the dynamics of changes in the course of a demographic revolution generates tensions. This takes place both at the level of an individual (collapse of ties that sustain family formation and its stability) and at a higher level of a country and society. One of the consequences of this process was a sharp drop in the number of children born per woman in developed countries. This fertility rate has fallen to 1.20 in Spain, 1.41 in Germany, 1.37 in Japan, 1.3 in Russia, and 1.09 in Ukraine. Results of surveys pointed to 1.92 as desirable for women in developed countries; in fact, mere sustainment of simple reproduction of the population requires on average 2.15 children per woman.

We conclude, therefore, that the richest and economically developed countries which went through the demographic transition 30–50 years earlier have by now failed in their main function — the reproduction of the population. Factors that led to it were the lengthening of the time needed to complete an education, the liberal system of values, family disintegration, and the decline of traditions and customs in the modern world. If this trend continues, the core population of developed countries is doomed to extinction and replacement by expatriates from more fertile ethnic groups. This is the strongest signal that demography sends to us [21].

The problem that arises when States attempt to find a way out of these paradoxes is that of management in the modern post-industrial world. The chaos of the market continues to work in small-scale phenomena operating on reversible processes of exchange. In times of demographic transition, the situation departs so far from equilibrium that an ordered behavior of the system breaks down and destroys both spontaneous self-organization processes and the organization of society by external forces. The conservative concept 'Business as usual' stops dominating in the turbulent times of demographic revolution, when social and economic relations are being redrawn. Consequently, the linear cause–effect approach to governance of society for establishing an equilibrium needs time, but time is in short supply owing to the speed of the transition. In view of this, governance and progress in theory in the post-industrial world require going beyond the limits of formulation of the problems in the present essay.

At the moment, current information technologies, the Internet and media most of all, have revolutionized the information space and posed new problems for the education system and governance of society. It is this system that partially realizes the universal interaction through exchange of information between generations, as formalized in the theory above. Thus, knowledge is becoming more and more a mass phenomenon, like literacy, healthcare, high culture, and even kitsch. However, modern media, TV first and foremost have become powerful tools for mind control in society, while information has become the most effective weapon.

If knowledge has become the purpose of training, then in the future **comprehension** will become the decisive factor. Therefore, the nurturing of cognition and innovation both in natural and 'unnatural' sciences should be channeled to the young generation and be implemented by young scientists. The system of education in developed countries has already become an element of economics, larger than the sector of industrial production; underestimation of this phenomenon when determining the priorities of development is not only shortsighted, but simply wrong. In this paradigm, the fundamental sciences — as the pinnacle of comprehension — resemble records in sports. Motivation of cognition, like motivation of the creativity of an artist, expresses the nature of the human mind. The material costs of a spiritual understanding of nature and the humans in it are an order of magnitude less than for implication of the acquired knowledge; besides, by virtue of the ingrained difficulty of planning the unknown, these costs fall outside short-term market interactions. However, both the direct and indirect effects of science on our life are immeasurably greater than what we see in the last lines in Fig. 7.

SCIENCE, INNOVATION, AND SOCIETY

EDUCATION ⟶ ⟶ ⟶ INNOVATION

	↑ Fundamental ⟶ science	↕ Applied ⟶ science	↓ Manufacturing and economy
Time:	100 years	10 years	1 year
Money:	1	10	100 $, Euro, ruble...
Motives:	cognition	benefit	development and income

Figure 7. The interaction among science, education, and industry in the modern world; ↑ — information.

6. Conclusion

The main conclusion following from the theory outlined above is that the growth and evolution of humans and mankind stem from the human mind. This idea was clearly formulated already by Aristotle in *Metaphysics*, where he argued that the main difference between humans and beasts is that "*All men by nature desire knowledge*." It is the collective interaction proportional to the square of the number of people in the world that determines, once a certain organization of the brain has been reached, this ability of the human mind to obtain, disseminate, and augment information dealing with the most diverse aspects of our activities.

With the advent of the world demographic revolution, the criterion of evolution and the goal of development for the foreseeable future will be the **quality of life**, not numerical growth. The quality of life stems from social organization, economics above all. This process will bring rapid development in the so-called developing countries, and we already see that in China, South Korea, Singapore, and Brazil. This optimistic scenario gives hope for overcoming the crisis in the making: the crisis will come mostly because understanding and responsible governance of society lag behind, and people are guided by the principle that "he who has power needs no brain."

Although the paths for the evolution of human society are in general known [17], but in a more remote perspective humankind is going to face the problem of the **quality of the human being**. From very early in its history, humankind strived, not without success, for ways to modify the qualities of animals and plants. At the beginning, this was achieved by artificial selection, but nowadays the breeder, better called genetic engineer, is armed with an array of powerful methods generated by modern molecular nanobiology. Their application to humans is proceeding, however, very cautiously, and even genetic diagnostics is already meeting with resistance from society, which is not ready to accept the consequences of a search of this sort. Obviously, this group of questions is much harder to answer than the problem of the quality of life. It inevitably returns to the fundamental principles of the nature of personality and human values, the meaning of our existence, and factors which impact on them. Sooner or later we will have to respond to these challenges brought to the fore by the progress of science now liberated from the fetters mounted by obsolete ideologies. A society which is found lagging behind in this competition will suffer from irretrievable losses in the future.

An analog of the difficulties we face today is the dilemma with the software of modern computers: the cost of hardware is much lower than that of software. This discrepancy between the power of productive forces, the progress of science, and industrial relations in today's open world — the common problem of control in a global world — appears to constitute a significant contradiction for the foreseeable future. These aspects encompass everything involving ecology, where partial approaches fail to result in solutions to problems as a whole. We discern this in the impasse of the 'powerless power' of weapons of mass destruction, as the idea of Carl von Clausewitz that "war is the continuation of politics by other means" has clearly become inapplicable.

We wish to remark, in conclusion, that the global problems are directly relevant for Russia as a country with subglobal geography, a long history, a multiethnic population, and a heterogeneous economy. This is the reason why seeking solutions in the context of such interdisciplinary global problems will require the participation of scientists in many disciplines from countries with different cultural heritages and intellectual traditions; hence, the importance of Russia's experience in knowledge synthesis. We therefore conclude our analysis with a comment on the priorities of modern science made by the former President of the Royal Society, Sir Robert M May [16]:

"It is interesting to speculate whether the denizens of other inhabited planets — if there are any — share the vagaries of our intellectual history: a fascination with the fate of the universe and the structure of the atom, lagging well behind interest in the living things with which we share our world.

A different, but related, question lies in human institutions' difficulties in taking action to address long-term problems at the expense of short-term interests (witness climate change). Such questions do not come readily under Medawar's rubric of science as "the art of the soluble", but they go to heart of humanity's future, which unwittingly entrains the rest of life on Earth."

The unbiased process of cognition in the sciences began during the Renaissance, first in astronomy and then in physics. The story of the problem of population growth resembles the story of the mechanics of the Solar System, which became a prototype of studies in celestial mechanics and stimulated the progress in mathematics. We can expect that the same methodology will be needed in the sciences dealing with society, so the experience and knowledge of global problems become doubly important.

Global problems know no national or economic borders: their geography encompasses the entire globe and they cannot be solved by generalizing partial solutions. It is very surprising, therefore, that the demographic revolution has not made it to the list of the most important events in the otherwise instructive analysis of the demographic future of the world in 2030, even though understanding the meaning of local changes in the world without it is hardly achievable [22]. This shows that reduction is not always helpful when we study complex systems, and therefore phenomenology, being based on an analysis of the actual data, can provide useful results. However, naive faith in the power of mathematics and blind imitation of physics will be barren no matter how powerful our computers or how rich our databases. The challenge to science lies precisely in this range of problems which touch on the root interests of human society.

The author dedicates this article to the warm memory of Vitaly Lazarevich Ginzburg. Vitaly Lazarevich offered his help and supported me in my research when others would only turn a blind eye. I will never forget presenting a report at Vitaly Lazarevich's famous seminar; his seminars profoundly influenced the course of science in our country. Meetings with him and the impact of his ideas were crucial factors for the fate of this paper.

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