COVER PAGE

Title: 2050: THE END OF THE GROWTH ERA?

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Summary

Contrary to common belief, both the Earth human population as well as its economic output have grown faster than exponential for most of the known history and most strikingly in the two last centuries. Indeed, this accelerating growth is consistent with a spontaneous divergence at the same critical time 2052 ±10 and with the same fractal patterns. This can be convincingly explained by an interplay between population, capital and technology producing an "explosion" in the population and in the economic output, even if the individual dynamics do not. This tremendous pace of growth has led to increasing worries about its sustainability as well as raising concerns that the human culture as a result may cause severe and irreversible damage to ecosystems, global weather systems, etc. On the other hand, the optimists expect that the innovative spirit of mankind will be able to solve such problems and the economic development of the World will continue as a succession of revolutions, e.g., the Internet, bio-technological and other yet unknown innovations replacing the agricultural, industrial, medical and information revolutions of the past. The existence of a spontaneous divergence around 2050 has the surprising consequence that even the optimistic view needs to be revised, since an acceleration of the growth rate contains endogenously its own limit in the form of a singularity, which can be interpreted as a transition to a qualitatively new behavior. Mankind may already have entered this transition phase along one of several possible paths leading to the new regime which can be one among several scenarios.

Representatives of national academies of science from throughout the world met in New Delhi, 24-27 October 1993, at a “Science Summit” on World Population. The participants issued a statement, signed by representatives of 58 academies on population issues related to development, notably on the determinants of fertility and concerning the effect of demographic growth on the environment and the quality of life. The statement finds that “continuing population growth poses a great risk to humanity,” and proposes a demographic goal: “In our judgment, humanity's ability to deal successfully with its social, economic, and environmental problems will require the achievement of zero population growth within the lifetime of our children” and “Humanity is approaching a crisis point with respect to the interlocking issues of population, environment and development because the Earth is finite”.

The rapid growth of the world population is indeed a quite recent phenomenon. It is estimated that 2000 years ago the population of the world was approximately 300 millions. It took more than 1600 years for the world population to double to 600 million and since then the growth has accelerated. It reached 1 billion in 1804, 2 billion in 1927 (123 years later), 3 billion in 1960 (33 years later), 4 billion in 1974 (14 years later), 5 billion in 1987 (13 years later) and 6 billion in 1999 (12 years later). The present purpose is to discuss what may be the future of Mankind if this growth continues. This will be based on a quantitative analysis of the evolution of the World population, of its economic output and of financial indices. The observed convergence of these distinct indicators point towards a drastic and unavoidable change of regime around 2050.

Let us start from Malthus' model, which assumes that the size of a population increases by a fixed proportion over a given period of time independently of the size of the population and thus gives an exponential growth. Take for instance the proportion of 2.1% per year or 23.1% per decade, corresponding to the all-time peak of the growth rate reached in

1970. This leads to a doubling time of 48 years. Starting from a population of say 1000, the population is 1.231 times 1,000=1,231 after one decade, 1.231 times 1.231 times 1,000 =1,515 after two decades, and so on. As we see, such an exponential growth corresponds to the multiplication of the population by a constant factor, here 1.231, for each additional unit of time, here ten years. It is thus convenient to visualize it by presenting the population on a scale such that successive values of the multiplication by a constant factor are equally spaced, which defines the so-called “logarithmic” scale that are used for all figures below. In the Malthusian exponential model, the logarithm of the population should thus increase proportionally to, i.e., linearly with, time. Figure 1 shows the estimated (logarithm of the) world population (obtained from the United Nations population division department of economic and social affairs) as a function of time. In contrast to the expected Malthusian straight line, we clearly observe a strong upward curvature characterizing a “super-exponential” behavior. A similar faster than exponential growth is also observed in the estimated GDP (Gross Domestic Product) of the World estimated by DeLong at the department of Economics at UC Berkeley, for the year 0 up to 2000. Over a shorter time period, a faster-than-exponential growth is also shown in figure 2 for a number of economic indicators such as the Dow Jones Average since 1790 obtained from the Foundation of the Study of Cycles (www.cycles.org/cycles.htm), the S&P index since 1871, as well for a number of regional and global financial indices since 1920, including the Latin American index, the European index, the EAFE index and the World index. The last five financial indices are obtained from Global Financial Data, Los Angeles, www.globalfindata.com. They are shown as their logarithm as a function of time, such that an exponential growth should be qualified by a linear increase.

These observed faster-than-exponential growths correspond to non-constant growth rates, which increase with population or with the size of economic factors. Suppose for instance that the growth rate of the population doubles when the population doubles. For simplicity, we consider discrete time intervals as follows. Starting with a population of 1000, we assume it grows at a constant rate of 1% per year until it doubles. This takes approximately one century. When the population turns 2000, we assume that the growth rate doubles to 2% and stays fixed until the population doubles again to reach 4000. This takes only 50 years at this 2% growth rate. When the population reaches 4000, the growth rate is doubled to 4%. The doubling time of the population is therefore approximately halved to 25 years and the scenario continues with a doubling of the growth rate every time the population doubles. Since the doubling time is approximately halved at each step, we have the following sequence (time=0, population=1000, growth rate=1%), (time=100, population=2000, growth rate=2%), (time=150, population=4000, growth rate=4%), (time=175, population=8000, growth rate=8%) and so on. We observe that the time interval needed for the population to double is shrinking very rapidly by a factor of two at each step. In the same way that 1/2 + 1/4 + 1/8 + 1/16+…=1, which was immortalized by the Ancient Greeks as Zeno's paradox, the infinite sequence of doubling thus takes a finite time and the population reaches infinity at a finite “critical time” approximately equal to 100+50+25+…=200 (a rigorous mathematical treatment requires a continuous time formulation, which does not change the qualitative content of the example). A spontaneous singularity has been created by the increasing growth rate! This process is quite general and applies as soon as the growth rate possesses the property of being multiplied by some factor larger than 1 when the population is multiplied by some constant larger than 1.

Such spontaneous singularities are quite common in mathematical descriptions of natural and social phenomena, even if they are often looked at as monstrosities. They are found in many physical and natural systems. Examples are flows of fluids, the formation of black holes, the rupture of structures and material failure, even in models of large earthquakes and of stock market crashes. The mathematics of singularities is applied routinely in the physics of phase transitions to describe the transformations from ice to water or from a magnet to a demagnetized state when raising the temperature.

The empirical test of the existence of singularities in the dynamics of the population or the economic indices rest on the way they increase up to the critical time. It turns out that they do so in a self-similar or fractal manner: for a given fixed contraction of the distance in time from the singularity, the population is multiplied by a fixed given factor. Repeating the contraction to approach closer to the singularity leads to the same magnification of the population by the same factor. These properties are captured by the mathematical law called a power law. Power laws describe the self-similar geometrical structures of fractals. Fractals are geometrical objects with structures at all scales and describe many complex systems such as the delicately corrugated coast of Brittany or of Norway, the irregular surface of clouds or the branched structure of river networks. The exponent of the power law is the so-called fractal dimension and, in the present context, quantifies the regular multiplicative structure appearing on the population, financial indices and on the distance in time to the singularity. Plotting the logarithm of the population as a function of the logarithm of the time from the singularity, a power law will appear as a straight line. This is shown in figures 3 and 4 for the World population, the World GDP and the financial indices shown in figures 1 and 2. Since the power laws characterizing the population and economic growth is expressed in time to the singularity, a value has to be chosen for this critical time. In figure 3, year 2050 is used which is close to the value obtained from a more sophisticated statistical analysis discussed later. For the financial indices, removing an average inflation of 4% or similar amounts does not change the results qualitatively but the corresponding results are not quantitatively reliable as the inflation has varied significantly over history with quantitative impacts that are difficult to estimate. The message to be extracted from this analysis is that the world population, as well as the major economic indices, has on average grown at an accelerating growth rate in good agreement with a predicted singular behavior. Singularities and infinities were anathema for a long time before it was realized that they are often good mathematical idealizations of many natural phenomena. They are not fully present in reality, only the precursory acceleration is there and foreshadows an important transition. In the present context, they must be interpreted as a kind of "critical point" signaling a fundamental change of regime.

At this point of the analysis, there is still a relatively large uncertainty in the determination of the critical time. As can be seen from the figures, an important reason lies in the existence of large fluctuations around the average power law behavior. The mathematical theory of power laws suggests an efficient way to take into account these fluctuations by generalizing the concept of a real exponent into a complex exponent. This can be shown to lead to so-called log-periodic oscillations decorating the overall power law acceleration. Fundamentally, this can be seen to replace the continuous self-similar symmetry into a discrete self-similar symmetry. For instance in the previous example, the population had a doubling growth rate each time the population doubled. In this case, the dynamics is self-similar only under change of times scales and change of growth rate performed with a multiplication by a power of two. This leads to discreteness in the acceleration of the population such that the power law is modulated by steps in its slope occurring at each magnification by a factor of 2, i.e. steps that are regularly spaced in the logarithmic representation. In reality, other factors than 2 can be selected by the dynamics. In addition, there are many other effects not taken into account in the analysis which introduce some blurring of the steps which then become smooth log-periodic oscillations as shown in figure 2 in dashed lines for the Dow Jones index.

There are fundamental reasons for introducing log-periodic corrections and complex exponents, deriving from the very structure of the theories describing fundamental particles at the smallest level on one hand and the organization of the entire complex systems on the other hand. Examples are fluid flows, formation of black holes, material failure and even stock market crashes. The presence of log-periodic oscillations derived from general theoretical considerations may provide a first step to account for the ubiquitous observation of cycles at many scales in population growth and in the economy.

Sensitivity analysis of the power law fits shown in figures 3 and 4 and of the log-periodic power law fit shown for the Dow Jones in figure 2 and tests of the statistical significance give a large improvement in the constraint on the position of the critical time, which is found to lie in the range 2042-2062 with 70% probability. Other authors, such as S. Kapitza from the Russian Academy of Sciences and Hanson from the department of Economics at George Mason University, have documented a super-exponential acceleration of human activity consistent with a singularity. Macro-economic models have also been developed that predict the possibility of accelerated growth. Maybe the simplest model is that of M. Kremer from Harvard, who notes that, over almost all-human history, technological progress has led mainly to increases in population rather than increases in output per person. In his model, the economic output per person is set equal to the subsistence level, which is assumed fixed. The output is supposed to increase with technology and knowledge and labor (proportional to population), for instance as proportional to their square root such that a multiplication of knowledge or of labor by 4 leads to a multiplication of output by only 2. The growth rate of knowledge and technology is assumed proportional to population and to knowledge, embodying the concept that a larger population offers more opportunities for finding exceptionally talented-people who will make important innovations and that new knowledge is obtained from existing knowledge. The resulting equation for the total population exhibits a growth rate, which is proportional to the population. As we have seen, this leads to a finite-time singularity. Kremer tested this prediction by using population estimates extending back to 1 million BC, constructed by archaeologists and anthropologists: he showed that the population growth rate is approximately linearly increasing with the population as expected. Our results extend and refine his by showing the consistency of the determination of the critical time, no only for the population but also for the World GDP and for major financial indices.

We have generalized Kremer's economic model by coupling labor, capital, technology/innovation and output/production to show that the finite-time singularities can be created from the interplay of these simultaneously growing variables, even if the individual quantities do not carry such singularities. This interplay also explains the observation that the population and the financial indices have the same approximate critical time 2052. A complementary approach is to incorporate a feedback between the population and the increasing “carrying capacity” of the Earth within Malthus' model. Such feedback comes from technological progress such as the use of tools and fire, the development of agriculture, the use of fossil fuels, fertilizers as well the expansion into new habitats and the removal of limiting factors by the development of vaccines, pesticides, antibiotics, etc. If the carrying capacity increases sufficiently fast, a finite-time singularity is obtained in the equations. In reality, the singularity will be smoothen out because the Earth is not infinite.

What could be the possible scenarios for mankind close to and beyond the critical time? A gloomy scenario is that humanity will enter a severe recession fed by the slow death of its host (the Earth). Hern, from the University of Colorado at Boulder and other scientists have gone as far as comparing the human species with cancer. This worry about human population size and growth is shared by many scientists, including the Union of Concerned Scientists (comprising 99 Nobel Prize winners) which asks nations to “stabilize population”.

Possible scenarios involve a systematic development of terrorism and the segregation of mankind into at least two groups, a minority of wealthy communities hiding behind fortresses from the crowd of “have-not” roaming outside, as discussed in a recent seminar of the National Academy of Sciences of the USA. This could occur both within developed countries as well as between them and developing countries. A more positive perspective is that “ecological” actions will grow in the next decades, leading to a smooth transition towards an ecologically integrated industry and humanity. Some signs may give indications of this path: during the 1990s, wind power has been growing at a rate of 26% a year and solar photo-voltaic power at 17% compared to the growth in coal and oil under 2%; governments have ratified more than 170 international environmental treaties, on everything from fishing to desertification. However, there are serious resistances, in particular because there is no consensus on the seriousness of the situation: for instance, the late economist J.L. Simon writes that “almost every measure of material and environmental human welfare in the United States and in the World shows improvement rather than deterioration”. The problem is not that Simon is wrong. By economic accounting, he is mostly right. The issues raised by the present analysis and that of others is that the approach to a finite-time singularity can be surprisingly fast in the last few decades preceding it. As a result, linear extrapolations will be grossly misleading, with catastrophic consequences.

Extrapolating further, the evolution from a growth regime to a balanced symbiosis with nature and with the Earth's resources requires the transition to a knowledge-based society, in which knowledge, intellectual, artistic and humanistic values replace the quest for material wealth. Indeed, the main economic difference is that “knowledge” is non-rival: the use of an idea or of a piece of knowledge in one place does not prevent it from being used elsewhere; in contrast, say an item of clothing by an individual precludes its simultaneous use by someone else. Only the emphasis on non-rival goods will ultimately limit the plunder of the planet. The incentives that people need to work and to find a meaning in their life should be found beyond material wealth and power. Some so-called “primitive” societies seem to have been able to evolve into such a state.

The race for growth may, however, continue and even be enhanced by new discoveries enabling mankind to fully exploit the vast resources of the oceans and even that of other planets, especially beyond our solar system. The conditions for this are rather drastic. For the planets, novel modes of much faster propulsions are required as well as revolutions in our control of the adverse biological effects of space on humans with its zero gravity and high radiation. New drugs and genetic engineering could prepare humans to the hardship of space leading to a new era of enhanced accelerated growth after a period of consolidation, culminating in a new finite-time singularity, probably centuries in the future.

Figure1: World population and World GPD over 2000 years from 0 to present in logarithmic scale as a function of time, such that a straight line qualifies an exponential growth. The straight segment helps the eye to show that the growth of both data cannot be accounted for by the exponential model.

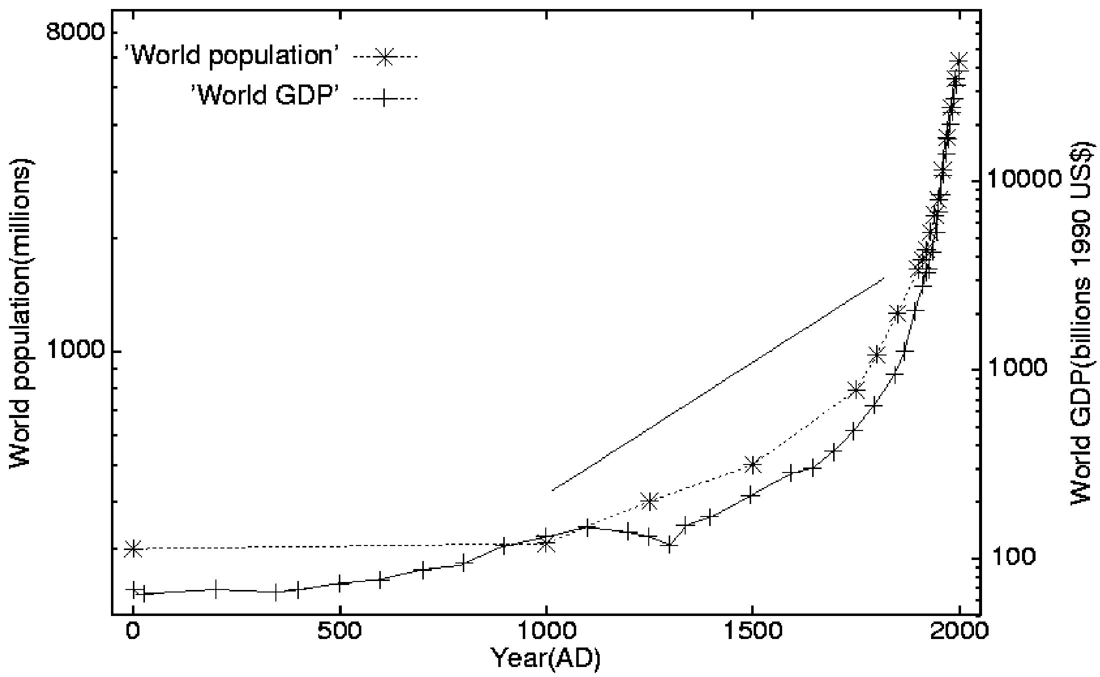

Figure 2: Financial indices in logarithmic scale as a function of time. The two largest time series, the Dow Jones extrapolated back to 1790 and the S&P index from 1871 are fitted by a power law shown as continuous lines. The log-periodic law (corresponding to a complex exponent of the power law) is shown only for the Dow Jones time series.

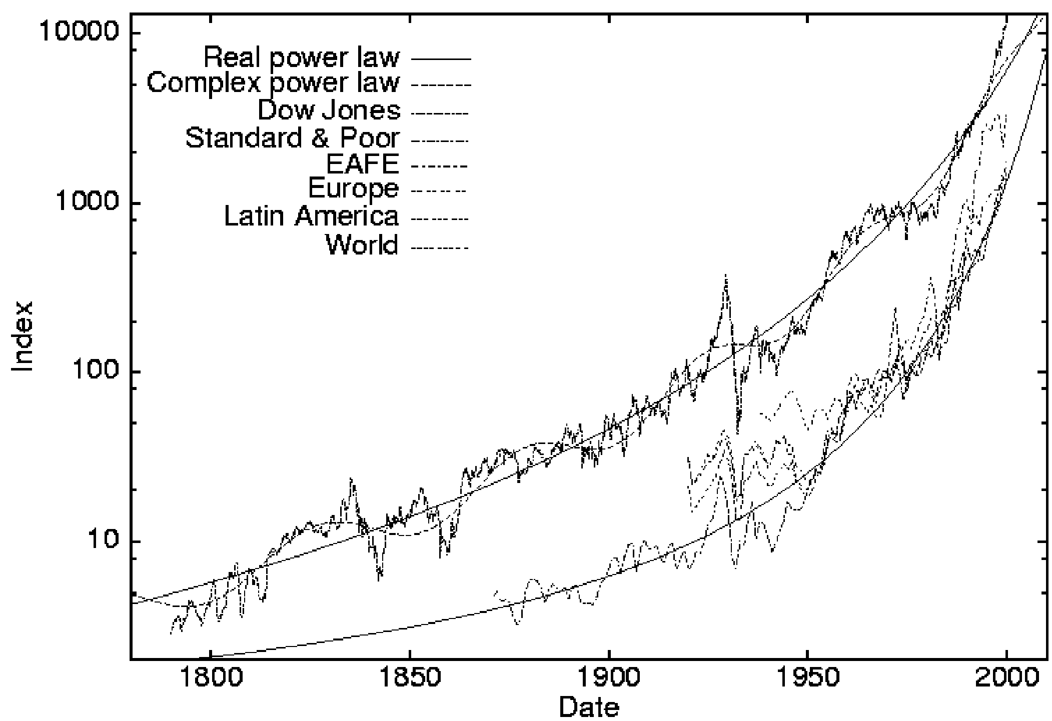

Figure 3: World population and World GDP (with a logarithmic scale) as a function of the time to the critical time t_c (with a logarithmic scale) such that time flows from right to left. The straight lines are the best fit of the data to power laws (see text).

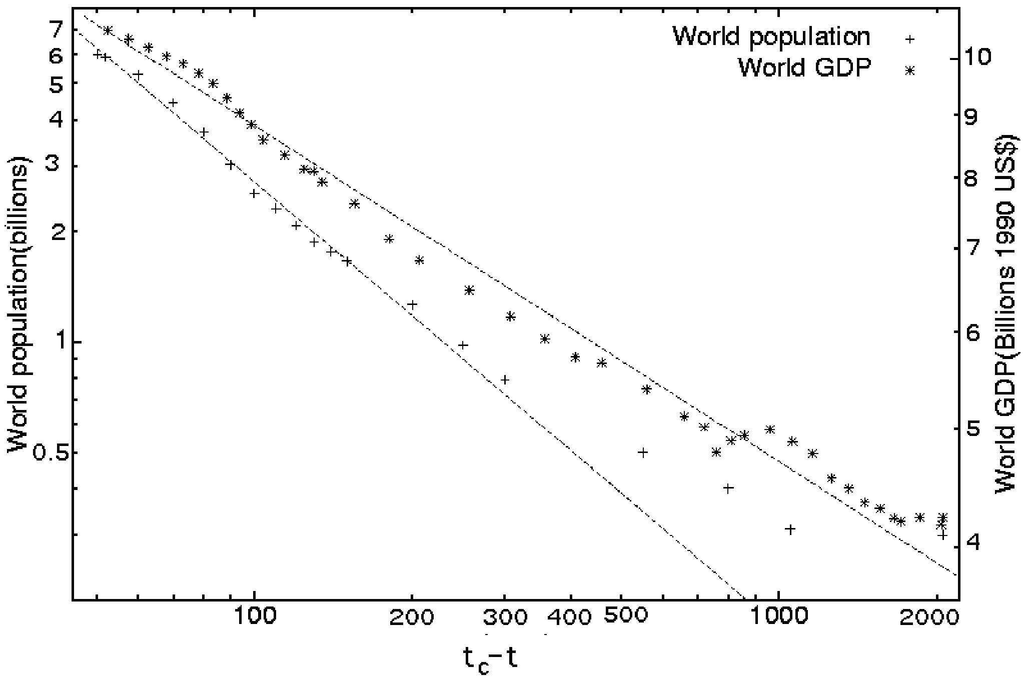

Figure 4: Logarithm of financial indices as a function of the logarithm of the time to the critical time t_c, such that times flows from right to left. The straight lines are the best fits, which qualify a power law behavior, as explained in the text.