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A possible declining trend for worldwide innovation

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Abstract

A comparison is made between a model of technology in which the level of technology advances exponentially without limit and a model with an economic limit. The model with an economic limit best fits data obtained from lists of events in the history of science and technology as well as the patent history in the United States. The rate of innovation peaked in the year 1873 and is now rapidly declining. We are at an estimated 85% of the economic limit of technology, and it is projected that we will reach 90% in 2018 and 95% in 2038.

Keywords: Technology limit; Innovation rate; Invention rate

There is a general consensus that technology is advancing exponentially, and that this advance will continue into the distant future. The basic assumption behind this view is that either there is no limit to technological advance, or if there is a limit, then we are far from reaching it. The history of technological innovation from the end of the Dark Ages to the present time is examined, and evidence is provided that we are closer to a technological limit than many people realize.

There are two different technological limits. The first limit is a physical one, due to the laws of physics, such as the impossibility of building a perpetual motion machine. The second limit is economic; it is physically possible to dig a canal from the Pacific Ocean to the Atlantic Ocean across the continental United States, but it is not economically feasible. This paper addresses the economic limit, as we will reach this limit before the physical limit.

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A useful indicator is needed to measure innovation as a function of time and to make projections into the future. No indicator is perfect, and some indicators are more useful than others. World per capita Gross Domestic Product (GDP) is a useful indicator of world economic health, but suppose only a listing of important products is available and not their dollar values. The criteria used for determining which products are important is subjective, but as long as a historical listing is consistent in applying the same subjective criteria for all products, then such a listing is useful. A world per capita GDP defined as the number of important products produced per year divided by the world population is still a useful indicator of world economic health, although obviously it is not as useful as the GDP indicator used today. Products vary widely in importance, some people are more productive than other people, and the proportion of the population that is productive varies with time. Similarly, events in the history of science and technology vary widely in importance, some people are more innovative than other people, and the proportion of the population that is innovative varies with time.

For the purposes of this paper, the rate of innovation is defined as the number of important technological developments per year divided by the world population. This result represents the innovation of an average person in developing new technologies each year. In a simplified model of the history of technology, in which the population remains constant, the rate of innovation is nearly zero at the dawn of civilization and then gradually starts to accelerate. Halfway to the technological limit, the rate of innovation reaches a maximum value and then starts to decline. As the technological limit is approached, the rate of innovation approaches zero, but it never reaches zero, so that the rate of innovation follows a bell curve. In reality, a number of different factors cause the rate of innovation to deviate from the idealized model. Some of these factors include an exponentially increasing population, war, key inventions, education, economic cycles, availability of raw materials, forms of government and religion.

In a model of technological development in which there is no technological limit, the rate of innovation should increase exponentially with only minor deviations due to the factors mentioned above. As more technologies are developed, people have a wider base of technologies to exploit, and they become increasingly more productive in generating new technologies. Thus, a plot of the rate of innovation over time can distinguish between a world with a technological limit and a world with no limit or with a limit that is so far away that it has little effect.

Fig. 1 shows the rate of innovation from the end of the Dark Ages up to the present time. The number of technology events per year comes from a list of 8583 important events in the history of science and technology compiled by Bunch and Hellemans [1]. Only the most recent 7198 events since the Dark Ages are used for the analysis presented in this paper. Population estimates used to generate the curves are those of McEvedy and Jones [2] up to the year 1900 AD, UN estimates [2] from 1910 to 1940, and US Census Bureau estimates [3] from 1950 to 2050. An unexpected aspect of Fig. 1 is that the rate of innovation reached a peak in the 19th century and then declined throughout the 20th century even with higher levels of education, major advances in science and the invention of the computer. This means that it was harder for the average person to develop a new technology in the 20th century than in the 19th century. There were more innovations during the 20th century than the 19th century, but the proportional increase in world population was greater. One of the most famous and prolific inventors of all time was Thomas Edison, and he lived from 1847 to 1931 during the golden age of innovation.

Fig. 1 also indicates a general trend of decreased rates of innovation during times of war and increased rates of innovation during times of peace. The rate of innovation declined during World

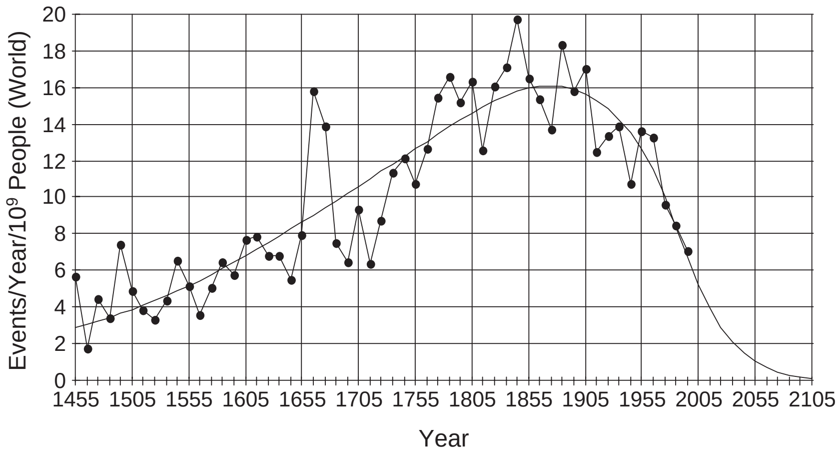

Fig. 1. Rate of innovation since the end of the Dark Ages. Points are an average over 10 years with the last point covering the period from 1990 to 1999. The smooth curve is a least squares fit of a modified Gaussian distribution to the data.

War I and II, and the highest peak at 1845 occurred during a decade with no major wars. Isaac Newton developed calculus and made important contributions to science at the peak in the second half of the 17th century during a time of peace. Major wars before and after this peak include the Thirty Year's War (1618–1648), Bishop's Wars (1639–1640), English Civil Wars (1642–1651), War of League of Augsburg (1688–1697), and the War of Spanish Succession (1701–1714).

Exponentially increasing population distorts the Gaussian distribution predicted by the simplified model of the rate of innovation for a world with a limit of technology. The rate of innovation, r, for a constant population is expected to vary with time, t, according to the following Gaussian distribution

$$r = (k/\sigma)\mathrm{Exp}\left\{ -(t-\mu)^2/2\sigma^2 \right\} \tag{1}$$

where k is a constant, σ is the standard deviation and μ is the mean. If the population is larger, then the peak in the bell curve is higher and narrower, so that σ decreases as population increases. Assuming σ is inversely proportional to a function of population, let

$$\sigma = C_1 P^{-C_2} \tag{2}$$

where P is the population and C_1 and C_2 are constants. Substituting Eq. (2) into Eq. (1) and renaming the constants yields

$$r = k_1 P^{k_2}\mathrm{Exp}\left\{ -k_3[P^{k_2}(t-\mu)]^2 \right\} \tag{3}$$

There is quite a bit of yearly variation in the rate of innovation that is not apparent when plotted by decade in Fig. 1. Performing a least squares fit of Eq. (3) to the yearly data from 1453 to 2003 gives k_1=15.11, k_2=0.3078, k_3=0.00001732 and μ=1832 where t is in years and P is the population divided by 10^9. Eq. (3), with the above constant values, is plotted in Fig. 1 as the smooth curve. Since the curve is a best fit of the data starting in 1453, it continues to decline prior to 1453 and does not model the peak in the rate of innovation achieved in ancient history. The curve peaks in the year 1873 and falls below three events per year per 10^9 population (which is the highest rate of innovation achieved during the Dark Ages) in the year 2024. It is not the intent to predict precisely when the rate of innovation will reach a specific level, as there are unknown uncertainties in the data, but to show the current rapid decline in the rate of innovation.

There are other possible indicators to use to measure the rate of innovation as a function of time such as dividing the number of innovations per year by the world per capita GDP or the world per capita spending on education. Any denominator that increases at a faster percentage rate than population will result in a rate of innovation that decreases more rapidly than illustrated in Fig. 1. World per capital GDP, as measured in year 2000 international dollars, was $850 in 1900 and $8175 in 2000 while world population grew from 1625 million to 6120 million [4]. As a result, world per capita GDP grew by a factor of 9.62 while population grew by a factor of only 3.77 during this time period, so that the ratio of these two factors is 2.55. It follows that the number of innovations when normalized to world per capita GDP declined 2.55 times more rapidly during the 20th century than when normalized to population. If total world per capita spending on education remained the same throughout the 20th century as a fraction of GDP, then the number of innovations when normalized to world per capita education expenditures would show the same decline as when normalized to world per capita GDP. Historical data on total world spending on education from private and public sources are not readily available, but the National Center for Education Statistics provides information on the total expenditures on education in the United States as a percent of GDP from the 1949–1950 school year to the 2001–2002 school year [5]. During this time period, the total US spending on education from public and private sources increased from 3.3% of US GDP to 7.7%. Expressed another way, US population increased by a factor of 1.90 while US per capita education expenditures, in constant 2001–2002 dollars, increased by a factor of 6.12. Education levels increased throughout the world, including third world countries, during the last century, and it is likely that total world expenditures on education did not decline as a fraction of world per capita GDP. A factor of 2.55 decline in the fraction of world per capita GDP spent on education from 1900 to 2000 is needed for innovations normalized to world per capita spending on education to match Fig. 1. Therefore, the decline in innovations normalized to population is clearly conservative when compared to innovations normalized to world per capita GDP, and it is likely conservative with respect to innovations normalized to world per capita education expenditures.

The decline in the rate of innovation illustrated in Fig. 1 is also conservative, and may understate the actual decline, in that a higher proportion of the innovations in recent years are simply improvements in existing technologies as opposed to the higher proportion of fundamental new technologies developed in the19th century. For example, Bunch and Hellemans list 37 separate events involving space shuttle missions between 1981 and 2003. The first space shuttle mission demonstrated new technology, but some people may argue that the following space shuttle missions are marginal improvements in existing technology and incorporating them in the analysis of the rate of innovation is double counting. If all the innovations representing minor improvements in previously existing technologies are deleted from the list, then the rate of innovation will decline more rapidly than indicated by Fig. 1, and therefore it is conservative.

The number of technology events per year, comparable in importance to at least the lesser events compiled by Bunch and Hellemans, predicted by Eq. (3) is P times r. Integrating P times r over all time yields the economic limit of technology. The level of technology for any year, T, as a percentage of the economic limit is

$$L_{\text{lower}} = 100\% \frac{\int_{-\infty}^{T} \text{Prd}t}{\int_{-\infty}^{+\infty} \text{Prd}t} \tag{4}$$

where L_{lower} is the level of technology illustrated by the lower curve in Fig. 2. It predicts we are at 85% of the limit of technology in 2004, reaching 90% in 2018 and 95% in 2038. The upper curve is a plot of

$$L_{\text{upper}} = 1.960(1.006963)^{(T-1452)} \tag{5}$$

where L_{upper} is an exponentially increasing level of technology. Eq. (5) is a least squares fit to the lower curve between the years 1453 and 1873. The exponential increase in the lower curve continued past the peak in the rate of innovation in 1873 due to the exponential increase in the world's population. In fact, the yearly percentage rate of growth in world population increased after 1873 and reached a peak in 1963 before declining [3]. There is a noticeable divergence of the lower curve from an exponential growth rate starting in the middle of the 20th century.

The patent is a basic unit of technology, and there are a precise number of patents issued each year by the US Patent Office as opposed to an imprecise number of innovations that are subjectively determined. Fig. 3 plots the rate of invention in the United States since the Patent Office opened in 1790. The rate of invention is defined as the number of patents issued each year to US residents by the US Patent Office [6] divided by the US population [7]. This measure of the rate of technology growth avoids one of the potential problems with using the world population for the rate of innovation in Fig. 1, in that a large portion of the world's population live in poor countries with rapidly expanding populations but contribute little to technology advancement. The peak in the rate of invention occurred in 1916, 43 years later than the peak in the rate of innovation in Fig. 1. There is an overall decrease in the rate of invention since this peak with a noticeable upswing occurring during

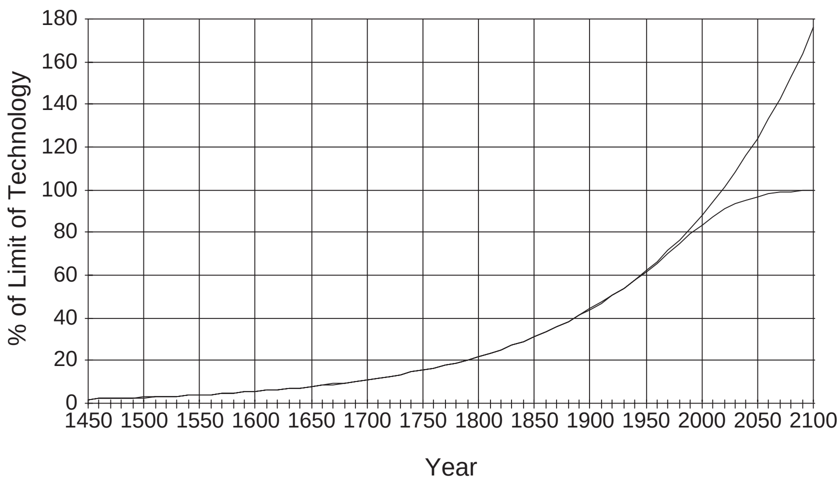

Fig. 2. Level of technology. The economic limit of technology is a horizontal line at 100%. The lower curve represents the predicted level of technology based upon the modified Gaussian distribution in Fig. 1. The upper curve is an exponential function fit to the lower curve between 1453 and 1873.

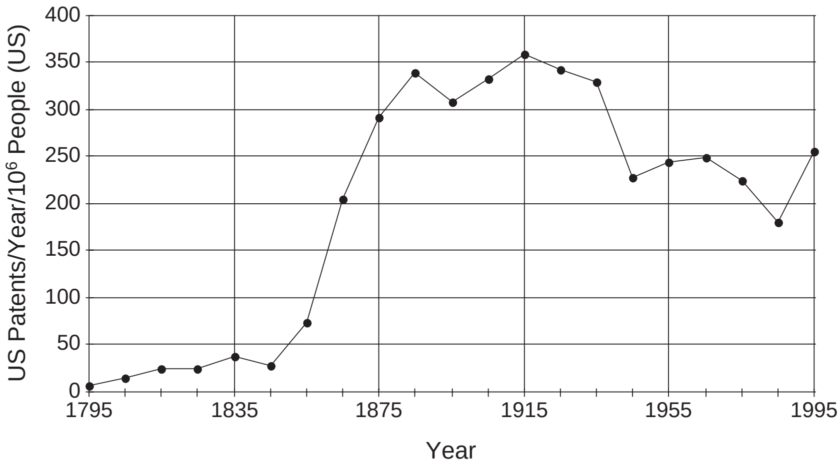

Fig. 3. Rate of invention. Points are an average over 10 years with the last point covering the period from 1990 to 1999.

the last decade. Fig. 3 provides additional evidence that we are approaching an economic limit of technology, as the rate of invention in the United States more closely matches a bell curve than an exponentially increasing curve.

An alternate interpretation of the data is that we are reaching the limits of the human brain rather than the economic limit of technology. For the first time in history people are bombarded with far more information than they can process, so sending them increasing amounts of random pieces of information will not increase their rate of innovation. Key inventions which increase the rate of innovation in the future may include technologies that filter and prioritize information, improve the capacity of the human brain, artificial intelligence or a genetically engineered, highly intelligent organism.

In conclusion, the evidence presented indicates that the rate of innovation reached a peak over a hundred years ago and is now in decline. This decline is most likely due to an economic limit of technology or a limit of the human brain that we are approaching. We are now approximately 85% of the way to this limit, and the pace of technological development will diminish with each passing year. These conclusions are controversial, but there are profound implications if they are true, and the following questions are included for the interested reader to ponder:

- What are the implications for the economy, government and society of declining rates of innovation?
- What standard of living corresponds to the economic limit of technology?
- Will the level of technology reach a maximum and then decline as in the Dark Ages?
- Did the failure of ancient people to invent the printing press cause the Dark Ages?
- Are there any key inventions that could reverse the current decline in the rate of innovation?
- Are improvements in the flow and processing of information the primary sources for increases in the rate of innovation?
- Are there any other reasons for the decline in the rate of innovation during the 20th century besides the approach of an economic limit of technology or a limit of the human brain?
- What is the relationship between innovation and democracy?
- Does democracy depend upon innovation?

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