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The Industrial Revolution Reconsidered: Hard Steps, The Great Filter, and Doomsday

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Abstract

The Hard Steps model is applied to argue that the Industrial Revolution (IR) heralded a terminal phase of human existence. Assuming six hard steps, the Kolmogorov-Smirnov method is used to pinpoint the start of the IR to ≈ year 1700. Once these hard steps were cleared, the global economy entered a growth spiral which, as in the multistage carcinogenesis model of cancer, will terminate once a lethal burden is reached. The Doomsday Argument suggests this happening within 900 years. Thermodynamic limits, however, indicate a limit in less than 400 years, and of about 26 years after invention an Artificial Super Intelligence (ASI). The IR may be the Great Filter, explaining the Fermi Paradox. Alternatively, current human observers may be living in an ancestorsimulation designed to study late-stage capitalism.

JEL classification

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Industrial Revolution, capitalism, economic growth, collapse

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1 Introduction

"It might not know it, but it's a dead species walking" (Gee, 2025, p.159)

The Industrial Revolution marked the beginning of the end phase of humanity. The history of modern humans, which stretches back roughly 300,000 years,[1] will likely come to a close sooner rather than later - likely in no more than 13,000 years. Before then, the extraordinary economic growth that has followed the Industrial Revolution will come to a halt, likely in far less than 400 years.

These are the central conclusions from this paper, which applies the Hard Steps Model—a framework originally developed in evolutionary biology to explain complex processes requiring multiple critical steps. The Hard Steps model is applied in conjunction with statistical Power-Law analyses, Bayesian probabilistic reasoning, econometric estimates, insights from multistage carcinogenesis modelling, and thermodynamic perspectives to substantiate the claim that the Industrial Revolution is a *Great Filter* — a trap that destroys civilizations shortly after they achieve exponential growth.

This conclusion suggests that the Industrial Revolution, often seen as a triumph of progress, may instead represent a probabilistic trap with significant risks. Based on an evaluation of the literature on the causes of the Industrial Revolution, it is concluded that at least six hard steps were required for it to occur.

Using the Kolmogorov-Smirnov (KS) method, the assumption of six hard steps is utilized to pinpoint the start of the Industrial Revolution to the year 1700, earlier than the broadly accepted 1750-1760 date - but closer to more recent estimates based on data on employment records from England and Wales.[2]

[1]Modern human ancestors separated from so-called archaic human groups between 1 million and 300,000 years ago (Bergström et al., 2021).

[2]See `https://www.varsity.co.uk/news/27372`

How long will this phase of industrial civilization, which began in 1700, last? Thermodynamic perspectives suggest the collapse of capitalism and economic growth within 400 years, while biological and Bayesian probabilistic reasoning suggest a time frame of 900-13,000 years. It is shown that if Artificial Superintelligence (ASI) is achieved and causes an economic growth explosion, a lethal limit could be reached in approximately 30 years after such an ASI is invented.

The upshot is that there is a possibility that human civilization has entered its final 10–20% of existence. If there is no Great Filter, then the only remaining hypothesis may be, following Bostrom (2003)'s Simulation Hypothesis, that human existence may be an ancestor-simulation designed to test whether a civilization can survive the metastasis of late-stage capitalism.

The rest of the paper proceeds as follows.

Section 2 presents the essential features of the Industrial Revolution as it pertains to economic growth, argues that at least six hard steps were necessary, identifies 1700 as a likely start of the revolution, and based on the likelihood of six hard steps, reconstructs GDP between the years 2 and 1699.

Section 3 uses multistage carcinogenesis modelling to understand the Industrial Revolution and subsequent aggressive economic growth as akin to cancer. It raises the warning of lethal burdens and collapse.

Section 4 investigates the question of how much time humanity has. This is in light of the consequences of the economic growth surge since 1700, the rather low probability of the revolution given at least six hard steps, and the insights from multistage carcinogenesis. Four approaches are used to predict the end: the Doomsday Argument, the Great Filter, Thermodynamic Limits to Growth, and empirical predictions.

Section 5 concludes by speculating whether a phenomenon like the Industrial Revolution can explain Fermi's Paradox, and if not whether human civilization is a simulation that will eventually be turned off.

2 Hard Steps to the Industrial Revolution

In this section, the Hard Steps Model is described in section 2.1. Then, in section 2.2, the Industrial Revolution is described with reference to the growth in world Gross Domestic Product (GDP). Given that world GDP follows a power rule distribution, the Kolmogorov-Smirnov (KS) method is used to determine a likely starting date for the Industrial Revolution, and the six hard steps that seem to have been necessary for the Industrial Revolution are discussed. Assuming that indeed six hard steps were needed for the Industrial Revolution, this section finally uses this assumption to reconstruct GDP data from year 2 to year 1699.

2.1 The Hard Steps Model

The emergence of an intelligent technological civilization on Earth occurred surprisingly late in the planet's habitable timeline, raising questions about the factors that delayed this development. The first life emerged around 4.5 billion years ago, and it is estimated that the Earth will be habitable for another one billion years.[3] (1 Gyr) or so (Carter, 2007). Thus, human civilization appeared in the last roughly 18% of the habitable lifetime of the planet.

Why did it take an intelligent, technological civilization so long to appear? The complexity of evolutionary processes and the multitude of factors influencing planetary habitability suggest that the emergence of such civilizations is an exceedingly rare and challenging event. For

[3]The Sun's core temperature rises by about 10% every billion years. In about 1 Gyr, the Sun will be so hot that Earth's oceans will evaporate and the CO_2 cycle will fail, rendering complex life impossible.

instance, if, following Verendel and Häggström (2017) one denotes the number of civilizations in the universe is Npq, where N = the number of planets that are habitable; p is the probability that on one of these a civilization develops and q is the conditional probability that it becomes a space-faring, galaxy-colonizing civilization. Current estimates suggest a vast number of potentially habitable planets with $\approx 2 \times 10^{19}$ terrestrial planets around Sun-like stars and $\approx 7 \times 10^{20}$ around M-dwarf like stars (Zackrisson et al., 2016). The lack of any evidence for any other civilization in the universe suggests that p is very small - implying that the rise of such is very hard (Bostrom, 2008; Verendel and Häggström, 2017).

In 1983 Astrophysicist Brandon Carter (see Carter (1983)) proposed a mathematical framework, the *Hard Steps Model*, to understand the lateness of humanity's arrival (Mills et al., 2025). As described by Watson (2025, p.1) "The hard steps model is a 'toy' mathematical representation of evolution towards complex life on Earth or Earth-like planets."

According to Carter (1983, 2007) the emergence of a technologically sophisticated civilization from a sterile planet requires passing through several (k) critical transitions - called Hard Steps, with a probability per unit time (λ_i). If the expected time for each step is much longer than the total window of time available (t), the probability $P(t)$ of having completed all k steps by time t, is approximated by (see Carter (2007, p.4)):

$$P(t) \propto t^k (\prod_{i=1}^{k} \lambda_i) \tag{1}$$

Equation (1) indicates that the likelihood of the transition follows a power-law relationship over time, where the exponent k represents the number of sequential Hard Steps required.

Carter (2007, p.1) argues that "the best fit with the fossil record" is six hard steps (k=6). If $k = 1$, a technologically advanced civilization should have appeared early. With $k = 6$, the model predicts that most technological civilizations will appear in the final 10–20% of their planet's life.

The six hard steps were (Carter, 2007, p.6): 1) abiogenesis; 2) the emergence of procaryote cells; 3) the emergence of eukaryotes; 4) combigenisis (sexual reproduction); 5) macromorphogenesis (large multicellular animals) and 6) "the emergence of our own anthropic civilization."

Criticism against Carter's Hard Steps model has been raised by Mills et al. (2025). They argue that Carter omitted the effect of the geological environment on Earth on the possibility that "steps" were viable. In their view "we find ourselves so close to the upper limit of Earth's habitability because this is where the geologically narrow 'window of human habitability' is located relative to Earth's total habitable lifespan' (Mills et al., 2025, p.2).

This criticism does not mean that the concept of hard steps is redundant - it merely conditions these on a shorter duration of planetary habitability - wherein the rise of a technological civilization can still be seen as an unlikely event. Even the more so, since, if the number of civilizations in the universe is Npq, the rapid emergence of life after the "geologically narrow window of habitability" arose implies at p may not be small, so that the current observation of $N = 1$ suggests that q may be very small. This may be because technologically advanced civilizations go extinct before becoming space-faring, or leaving durable techno-signatures.

There are may reasons why technologically advanced civilizations may go extinct before their existence becomes visible in the galaxy. Ord (2020) for instance considered the probability that human civilization goes extinct in the next century. He estimates that there is a 1 in 6 chance of an existential catastrophe befalling humanity within the next century, with risks stemming from technology as more significant than that posed by natural disasters; he in particular identifies Artificial Intelligence (AI), engineered pandemics and nuclear war as high risks.

These anthropogenic extinction risks have been all been accelerated - if not directly caused

- by the unprecedented economic growth trajectory that the world has been put on by the Industrial Revolution. The latter is, however, seldom recognized as the potential beginning of the end of humanity , but rather as an event that heralded the beginning of the end to poverty and suffering in the world. This is, of course, understandable. As Ord (2020, p.18) points out "the industrial period has seen all of humanity become more prosperous, educated and long-lived than before."

The problem is that the Industrial Revolution, as section 2.2.1 below sets out, catalyzed historically unprecedented rates of economic growth which, by doubling the size of the global economy approximately every 38 years, has been placing potentially lethal burdens on planetary systems. While it is easy to notice the progress in wealth, and in the education and life expectancy that this has afforded, it is less easy to follow large scale processes evolving at exponential growth rates. Rees (2023, p.19) points out that "*People don't generally think in terms of discontinuous behavior – lags, thresholds (tipping points), and other non-linearities; we don't 'get' complexity.*"

In this light the Hard Steps Model remains a useful framework for examining the occurrence or incidence of the Industrial Revolution, which occurred roughly 300,000 years into the existence of modern humans (Bergström et al., 2021), and has happened only once in history. This late, and singular occurrence suggests that, it may also have been somewhat unlikely. It suggests that various hard steps had to be completed before it could take place - and that, given that q is likely very low - it will not complete all the hard steps for humans to become spacefaring.

The next sub-section (2.2) describes the lateness and singularity of the Industrial Revolution, while sub-section 2.3 applies the Hard Steps model to identify at least 6 ($k = 6$) hard steps for the Industrial Revolution.

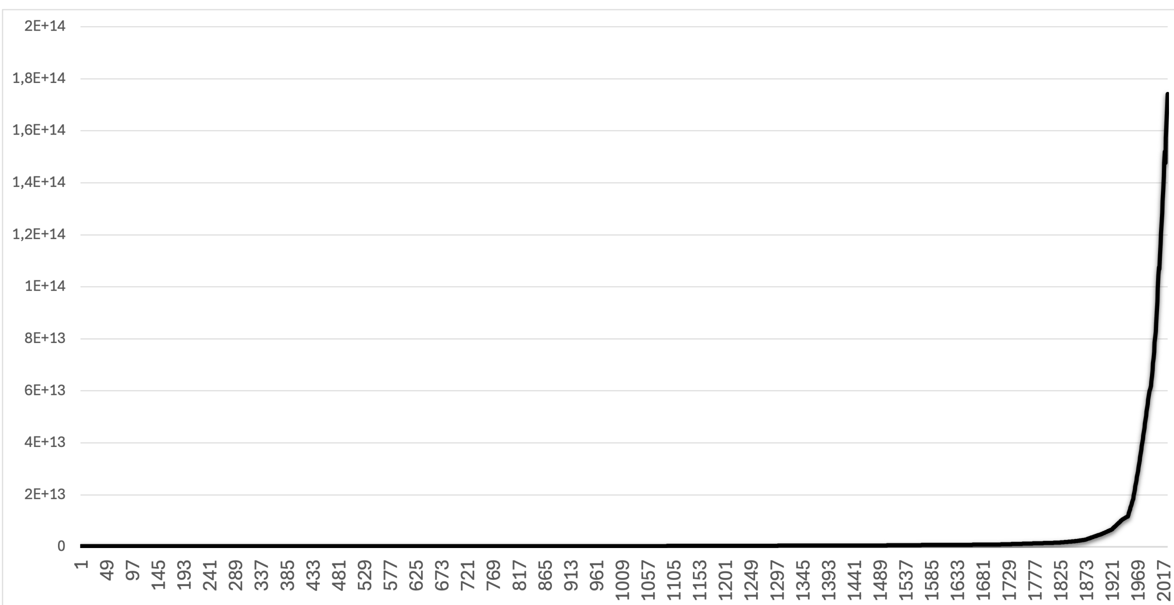
2.2 The Industrial Revolution and Growth Take-Off

The Industrial Revolution has been described as the most important event in economic history (Bryan, 2025). It was also very unlikely.

2.2.1 GDP over the Long-Run

Figure 1 depicts the take-off in economic growth, as reflected global GDP (adjusted for inflation), between the year 1 and 2024. It shows a seven-hundred fold increase in two millennia. Most of this increase occurred since 1700-1750.

Figure 1: Global GDP adjusted for inflation, 1 to 2024, US $



Source: Author's compilation based on data from Our World in Data.

For most of human history, GDP was at or below the subsistence level. Humans lived for thousands of years in a stagnant, zero-growth economy, until a particular point in time when economic growth took off. For most of the time, the world has been on a trajectory of exponential economic growth. During this period, the size of the world economy, along with related measures such as population and energy consumption, roughly doubled every

35 years.

The scale of human activity is now impacting Earth systems so substantially that a new geologic epoch is said to have begun in the 1950s: the Anthropocene (Waters and Turner, 2022).

2.2.2 When did the Industrial Revolution Begin?

When did the Industrial Revolution take off? According to conventional wisdom, "Textbooks typically mark the Industrial Revolution as beginning around 1760, when mills and steam engines proliferated, and technologies such as the spinning jenny were created" (Hall, 2024).

If, instead of measuring the Industrial Revolution's start by considering the proliferation of technologies such as mills and steam engines, one treats GDP as the result of the Industrial Revolution, then the information in Figure 1 can be used to obtain a statistical estimate of when the Industrial Revolution began.

The curve of GDP over time, depicted in Figure 1, follows a *Power Law*, also referred to in economics as a *Pareto distribution*.

The probability that any GDP is greater than some value x can be modelled by (see Gabaix (2009, p.256)):

$$P(GDP > x) = kx^{-\alpha} \tag{2}$$

In equation (1), α is the Pareto exponent. It can typically be estimated by OLS regression of the log of the rank of GDP in a year, against the log of the size of GDP in that year, i.e.:

$$\ln(\text{RankGDP})_t = C - \alpha \ln(\text{GDP})_t \tag{3}$$

OLS on log-log plots often underestimates the standard error, as put by Gabaix (2009, p.284) "the standard error returned by OLS software is wrong because the ranking procedure makes the residuals positively autocorrelated." Hence, it is recommended to apply *Gabaix's Rank Correction* (Gabaix and Ibragimov, 2008) to reduce the bias in the tail, which requires modifying equation (2) to

$$\ln(\text{RankGDP} - 0.5)_t = C - \alpha \ln(\text{GDP})_t \tag{4}$$

Using the data from Figure 1, OLS estimates with the Gabaix Rank Correction yield an estimate of $\alpha = 0.82$. It confirms that the distribution of GDP over the last 2023 years is highly top-heavy: most of GDP has been produced in recent years.

The top-heaviness of the distribution of GDP over time means that Figure 1 shows an almost straight horizontal line for much of the time period, and then, after some time point, turns into a power-law tail. This is typical as noted by Clauset et al. (2009, p.662) since, "in practice, few empirical phenomena obey power laws for all values of x. More often, the power law applies only for values greater than some minimum x_{min}. In such cases, we say that the tail of the distribution follows a power law."

If one defines the beginning of the Industrial Revolution as the time point when the distribution of GDP over time turns into a power-law, then one needs to identify the lower bound (x_{min}) from where the tail of the distribution in Figure 1 follows a power-law.

Clauset et al. (2009, p.672) recommends the Kolmogorov-Smirnov (KS) method for estimating x_{min}. This method essentially applies an iterative procedure to find a threshold x_{min}

such that the data values $x \geq x_{min}$ fit a Pareto distribution as closely as possible. It locates $x_{\min}$ that minimizes what is known as the KS distance between the empirical distribution and a hypothesized power-law model.

For each candidate $x_{\min}$, the power-law exponent α was estimated using the Maximum Likelihood Estimator (MLE) proposed by Hill (1975):

$$\hat{\alpha} = 1 + n \left[\sum_{i=1}^{n} \ln \frac{x_i}{x_{\min}} \right]^{-1}$$

where n is the number of observations $\geq x_{\min}$ and x_i are those individual GDP values. This determined that in the present case, $\alpha \approx 1.6$.

The Kolmogorov-Smirnov (KS) Statistic D was calculated to measure the maximum distance between the empirical cumulative distribution function (CDF) $S(x)$ and the model's CDF $F(x)$:

$$D = \max_{x \geq x_{\min}} |S(x) - F(x)|$$

where $F(x) = 1 - \left(\frac{x}{x_{\min}}\right)^{-(\alpha-1)}$.

The $x_{\min}$ value that yielded the minimum KS distance D was selected as the optimal threshold for the Pareto tail. This value occurs at \$871,056,000,000, which is that of year **1700**. Soon afterwards, world GDP entered a super-scaling phase. The $\alpha \approx 1.6$ indicates an extreme level of concentration in world GDP over time, with most of the increases in GDP occurring towards more recent times.

Thus, based on this rather simple statistical analysis, it can be concluded that the Industrial Revolution, from the point of view of GDP data, started around the year 1700 - in other words, the final hard step was cleared around 1700. This finding is consistent with recent research reported by the University of Cambridge into the start of the Industrial Revolution, using data on occupations in England and Wales.[4] This found that "*that the key period for the shift from the primary to the secondary sector was from 1600-1700, not 1750-1850 as 100 years of scholarship has assumed.*"

In conclusion, one may posit, from the analysis in this section and drawing on insights from the power-law, that the Industrial Revolution began around 1700, which explains the rapid take-off in economic growth that occurred, especially since 1750.

2.2.3 What Caused the Industrial Revolution?

The causes of the Industrial Revolution and why it first took place in the UK have spawned a large literature. To the extent that there is consensus, the Industrial Revolution is explained as the outcome of the confluence over time of a range of factors, all of which had to be in place at the right time and place. Each of these can be seen as a "hard step" that first needs to be taken and put in place, and a certain number of hard steps need to have been taken, before an industrial revolution could have taken place. There is no simplistic single cause of the Industrial Revolution.

Of course, the Industrial Revolution depends on the emergence of an intelligent species such as humans. This was hard, and not automatic - it took 4,5 billion years of evolution for humans to eventually emerge, almost at the end of the planet's habitability. And once this happened, it still took around 300,000 years for an industrial revolution to happen. This long time scale suggests that the emergence of an industrial revolution and economic growth take-offs are extremely difficult, requiring many hard steps.

Galor (2011) has proposed a "Unified Growth Theory" to explain the Malthusian Stagnation that characterized human society for most of its history - reflected in the flat portion of the graph in Figure 1 - as well as the occurrence of the Industrial Revolution and subsequent

[4] Source: `https://www.economiespast.org/`

growth take-off. Based on this, the next sub-section identifies the hard steps required for the Industrial Revolution.

2.3 Hard Steps in Growth Theory

In Figure 1, before the Industrial Revolution and the growth takeoff that occurred around 1700, GDP per capita was stagnant, as shown by the flat portion of the graph. This period is known as the Malthusian Stagnation. During this period, technological progress was countered by population growth. Following Galor (2011), this can be modelled as:

$$y_t = \frac{A_t \cdot L_t^{\alpha} \cdot X^{1-\alpha}}{L_t} \tag{5}$$

Where y_t is GDP per capita at time t; A_t the level of technology; L_t the population size; and X the amount of fixed land.

The Malthusian Stagnation can be seen to obtain if increases in technological progress (A_t) leads to a proportional increase in population (L_t), so that y_t remains constant.

If technological innovation is a function of population size (more "tinkers" and "geniuses" follows from a larger population) as well as of the quality of that population, the the growth in technology can be written, following Galor (2011, p.155), as:

$$g_{A,t+1} = \frac{A_{t+1} - A_t}{A_t} = \phi(e_t, L_t) \tag{6}$$

From this the first two hard steps towards the Industrial Revolution can be identified: Scale and Knowledge. A larger population (L_t) produce more ideas. And more knowledgeable or skillful human capital (e_t) makes those ideas more sophisticated and effective.

A third hard step is a demographic transition. As g_A slowly accelerates, it will reaches a threshold (the third hard step) where it starts to change the returns to education. This hard step can be made explicit by specifying the utility function where parents choose between the number of children (n_t) and the education per child (e_{t+1}) as :

$$u_t = (c_t)^{\gamma} \cdot (n_t \cdot w_{t+1})^{1-\gamma} \tag{7}$$

Where w_{t+1} is the future potential income of the child, which depends on their education (e_{t+1}).

Now, when technological progress (g_A) in (2) becomes fast enough, a quantity strategy (having many children to work the land) is jettisoned in favor of a quality strategy, having fewer but more highly educated children. As Galor (2011, p.152) explains, education "lessens the adverse effect of technological progress. That is, technology complements skills in the production of human capital." Thus, the third hard step is a demographic transition.

With the hard step of the demographic transition reached, the drag of L_t is removed from the denominator in equation (1). Now GDP per capita growth can be written as:

$$g_y \approx g_A - \Delta n$$

Since birth rates (Δn) fall while technology (g_A) continues to accelerate due to high human capital, g_y (GDP per capita growth) explodes.

The hard steps of reaching a population density high enough to sustain an idea market, and of achieving technological complexity to facilitate a demographic transition, contain various preconditions or ancillary hard steps. For instance, various hard steps served as "engines of technological progress" (Galor, 2011, p.172). One such engine-like hard step was the emergence of appropriate institutions - rules of the game - that facilitate investment and co-operation in technological innovation and adoption, such as property rights, inclusive governance and finance (Acemoglu and Robinson, 2013; Acemoglu et al., 2023). See also Landes (1999); Landes et al. (2010).

A related, further engine-like hard step, referred to by Mokyr (2016) as a "culture of growth," was, among others, the realization that scientific knowledge can usefully be applied to create technology, and that technology in turn can facilitate further discovery and use of scientific knowledge. Technology can, in this view, be seen as a "mutation" that allowed humanity to bypass the natural growth-suppressors of the Malthusian trap.

What is not present in Galor (2011) but also constituted an important hard step towards the Industrial Revolution was gaining access to sufficient and affordable energy sources, such as oil and coal. To a large extent, the Industrial Revolution was an energy revolution. Smil (2017) documents that the transition from wood to coal happened so quickly that it outpaced humans' understanding of the carbon cycle, essentially "tricking" the economy into a growth rate and carbon emissions it cannot sustain.

There were thus at least half a dozen hard steps in the configuration of society, the economy, technology, and energy that needed to be covered before the Industrial Revolution could take off.

The Industrial Revolution triggered an economic growth take-off, because the hard steps discussed in the previous paragraph, once they were met for the first time in Northwestern Europe, lead to the emergence of capitalism- an economic system in which the pursuit of private profits embeds the need for economic growth as an essential condition of the system(Naudé, 2023). Key in this regard was the formation of corporations - which became independent long-loved legal persona - that could leverage technology, finance, energy and labor to radically intensify the extraction and exploitation of natural resources.

The beginning of capitalism - which spawned the Industrial Revolution - predates the start of the Industrial Revolution. According to Monbiot and Hutchison (2024) the birth of capitalism occurred around the year 1450, on the island of Madeira, claimed by Portugal. They argue that Madeira was the first place where the three essential pillars of capitalism —commodified land, commodified labor, and commodified money — came together simultaneously.

In light of the finding in the previous sub-section of 1700 as the start of the Industrial Revolution, the Monbiot-Hutchinson estimate of 1450 as the start of capitalism, can be considered the conception phase for the Industrial Revolution which occured 250 years later - by which time capitalism has captured the machinery of the nation-state and global finance. For instance, in the period 1600 - 1700 several decisive institutional milestones were reached which helped crossing the institutional hard-step already discussed.

These include the establishment in 1602 of the Amsterdam Stock Exchange and the Dutch East India Company (VOC)[5] - the world's first multinational corporation and the first to issue publicly traded stock (Nijman, 1994); the establishment of the Bank of England in 1694, which heralded the moment the the state itself became an engine for capital accumulation and growth (Roberts and Kynaston, 1995); and the "Enclosures Acts" in England which during the period 1600-1700 resulted in the country's Parliament authorizing "4,000 acts of enclosure on behalf of the rising class of gentry, allowing them to expropriate about 15 percent of all of English common lands for their private use" (Bollier, 2015). This hastened the commodification of labor and generated the "surplus" labor needed in the Industrial Revolution's urban factories.

The commodification of land, labor and money set in motion an institutional development which ultimately tied the money supply to interest-bearing debt and created a demand for future energy (Hagens, 2020). Because debt grows exponentially, the underlying economy must also grow exponentially just to prevent a systemic banking collapse. This effectively

[5]By 1650, the VOC was the largest private corporation that had ever existed, being valued in modern prices close to US$7.9 trillion —larger "than the top 10 modern tech giants combined" - see Fisk (2017).

hard-coded the t^k power law into the modern economy's DNA.

Galor's model shows that once this transition to embedded economic growth occurs, the growth is irreversible and exponential. With hindsight, and as will become clear in this paper, a relevant question is whether *all* the necessary and sufficient steps were cleared for a sustainable Industrial Revolution and subsequent economic growth. The Industrial Revolution, which occurred around 1700, may have been, in a sense, premature.

2.4 Reconstructing GDP before the Industrial Revolution

Section 2.3 argued that there were at least half a dozen hard steps ($k = 6$) in the configuration of society, economy, technology and energy that needed to be covered before the Industrial Revolution could take off. This information can be used to reconstruct GDP in the period 1-1700, before the Industrial Revolution took off. This may be useful to do, since the estimates shown in Figure 1 for the period show very little variation - for most of this period, GDP estimates provided by economic historians and reported by *Our World in Data* are essentially constant. This reflects the imputations made to overcome the lack of reliable data records in deep history.

Assuming that the analysis in section 2.3 can be taken as roughly accurate, and that $k = 6$, then one can first estimate the power law in (1) on the existing GDP data as:

$$\ln(GDP) = k \ln(t) + \ln(C) \tag{8}$$

Here, the slope (k) provides an estimate of the number of critical hard steps the system had to clear before the transition (Year 1700) occurred. Using current generally accepted data on GDP between year 1 and year 1700, as provided by *Our World in Data* (OWD), a log-log regression (8) finds an estimate for $k = 0.6$. Clearly, this does not correspond to *a priori* expectation based on the discussion in the previous sections of $k = 6$. It even suggests that the currently accepted GDP data over the period imply that there was only approximately a single hard step, if the estimate is rounded off, successfully completed during this 1,700-year window.

The question then is: what values of GDP between the years 1699 and 2 would yield a regression of equation (8) with $k = 6$?

To estimate reconstructed GDP values from Year 2 to Year 1699 using a power-law model with an exponent of 6, GDP growth will need to follow a hockey stick trajectory connecting the known starting point (Year 1) with GDP $\$247,430,000,000$ to the known year 1700 GDP of $\$871,056,000,000$ (adjusted for inflation).

Using the power law relationship $GDP(t) = GDP(1) + C \cdot (t-1)^6$ one first needs to fix the constant, C. This is easy to calculate as :

$$871,056,000,000 = 247,430,000,000 + C \cdot (1700 - 1)^6$$

$$623,626,000,000 = C \cdot (1699)^6$$

$$C = \frac{623,626,000,000}{1699^6} \approx 2.59277 \times 10^{-8}$$

From this, reconstructed GDP estimates from year 2 to 1699 can be calculated. Table 1 compares the reconstructed estimates using $k = 6$ as the power law exponent with the estimates as provided by Our World in Data.

Comparison of the reconstructed GDP data from 2 to 1699 shows that the estimates are, until 1600, somewhat smaller, implying a much more pronounced growth acceleration towards the end of the period, i.e. towards 1700. In other words, world GDP grows extremely slowly

Table 1: Comparison of Reconstructed GDP estimates, 2 - 1699

Year	GDP - OWID Estimates	GDP - Reconstructed Estimates
1	247.430.000.000	247.430.000.000
1000	284.535.000.000	273.202.519.061
1500	582.932.000.000	541.583.308.318
1600	777.828.000.000	680.795.887.379
1700	871.056.000.000	871.056.000.000

for the first millennium, and accelerates rapidly from 1600 as it approaches the industrial transition in 1700.

Interestingly, this process, the beginning of the Industrial Revolution in 1700, and the subsequent exponential growth take-off in the decades following, match the Nordling-Nunney model of the incidence of cancer. This suggests that the emergence of the Industrial Revolution can be analyzed with the same tools that have been used to understand the growth of cancer. This will be illustrated in the next section.

3 Industrial Revolution as a Cancer

The pattern of economic growth depicted in Figure 1 is very similar to the occurrence of cancer over time in humans. In particular, the probability of cancer appearing at age t is not linear (Nordling, 1953). Similarly, the probability of an Industrial Revolution (IR) appearing at time t is also not linear. In the case of cancer, this is because a cell requires k independent mutations to become cancerous. Similarly, in the case of the IR, it required k hard steps before it could occur.

3.1 Multistage Carcinogenesis

According to Nordling (1953)'s evolutionary model of multistage carcinogenesis (EMMC), a cell must accumulate a specific number of independent mutations to cause cancer. As described by Nunney (2020, p.1581), "the model assumes that a number of driver mutations (inherited and/or resulting from somatic mutation) must accumulate in a single cell for cancer to arise. A clear prediction of this model is that, if all else is equal, more somatic mutation will lead to an increased cancer risk."

If cancer were the result of a single random event, the risk would be constant over time (a flat line), and the cumulative probability would be linear. However, because it is multi-stage, the probability grows polynomially. This is analogous to an industrial revolution occurring over human history - it is not the result of a single random event.

In the case of the incidence of cancer, $I(t)$, the probability of a tumour appearing at age t, can be represented by a Power Law function such as:

$$I(t) = c \cdot t^k \tag{9}$$

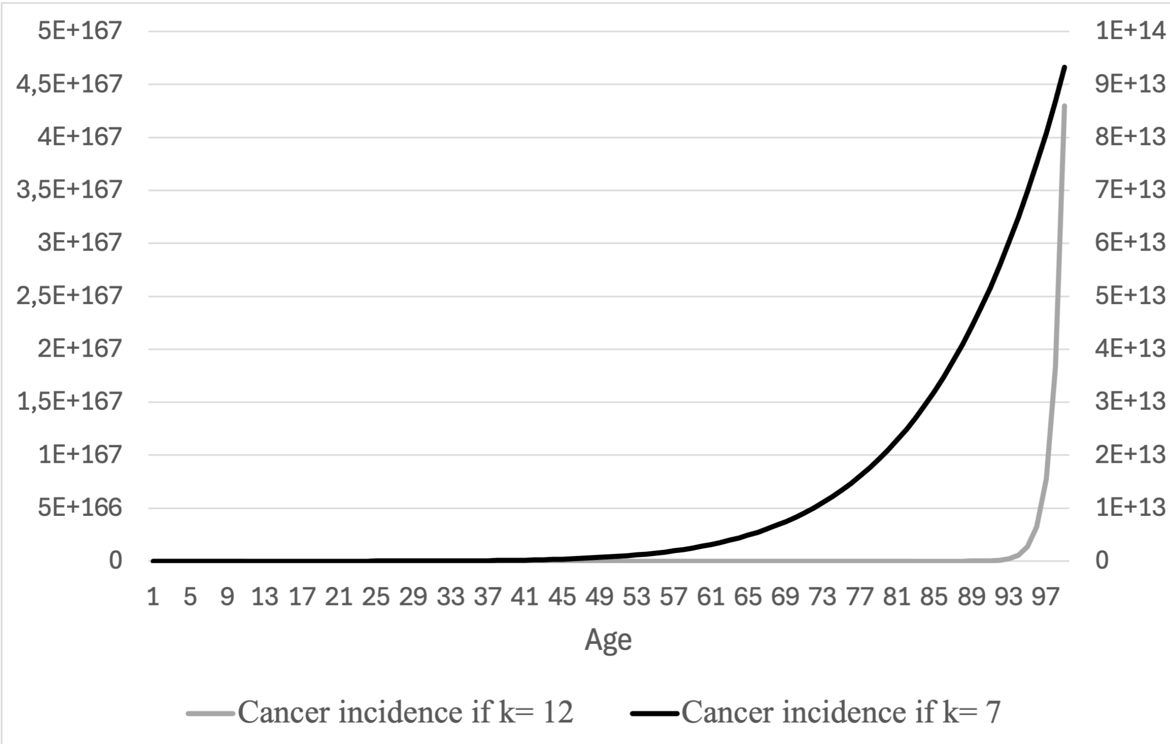
Where k is the power-law exponent and c a constant, which reflects the product of the mutation rates at each stage and the number of cells at risk. It is typically very small.

The power-law exponent (k) is the number of sequential mutations required to transform a healthy cell into a malignant one, minus one ($k = n - 1$). Figure 2 depicts the incidence of cancer, $I(t)$, over a human life-time. The similarity to the depiction of GDP per capita growth in Figure 1 is clear.

In Figure 2, $k = 7$, hence the incidence grows at the seventh[6] power of age (t^7). This means

[6]Nunney (2020, p.1585) reports that k differs between cancer types, ranging from 2 in the case of

Figure 2: Incidence of Cancer over a Human Lifetime, with k =7 and k =12



Source: Author's compilation based on equation (1) with c=1, k=7 assumed values

the risk at 60 is 729 times higher than at 20. This creates the hockey stick effect where nothing happens for decades, and then the system "explodes."

Similarly, in the case of global economic growth, nothing happened for millennia, and then after a particular point in time (1700), an Industrial Revolution occurred, and the system transitioned into a new phase. In both the case of cancer and the IR, if the steps (k) to an outbreak are many and difficult, the "transformation" (becoming cancerous or triggering an IR) will almost always happen very late in the available time window. In other words, because the hard steps are rare and independent, the probability of all occurring "bunches up" toward the end of a civilization's life, just like cancers tend mostly to occur in old age.

There is a further useful insight from comparing the economic growth take-off with the breakout of cancer. Nunney (2020) explained the "Peto's Paradox," the apparent contradiction

retinoblastoma to "10 or more in other cancers."

that a blue whale, with many more cells than a human, does not get cancer many times more often. Nunney (2020) showed that for an organism to grow larger or live longer, it must increase its k (the number of hard steps), which in the case of the whale are tumour-suppressor genes - "immune policing." An increase k, pushes the exponential explosion (cancer incidence) further to the right on the timeline. This is shown in Figure 2 above, where the line tracks cancer incidence for $k = 12$.

In this case, the risk at age 60 is much lower than in the case of $k = 7$. It is also the case that the more hard steps there are to overcome, the steeper and more dramatic the eventual transition is. This begs the question: *was the Industrial Revolution premature?*

If more and harder steps were required, and it only occurred in, say 2100 rather than 1820, would the resulting economic growth explosion have been quantitatively and qualitatively different? Would it perhaps have meant a longer-lived human civilization than a world in which the Industrial Revolution occurred around 1700? Was the Industrial Revolution premature? Sears (2020, p.580) postulated an "anarchy-technology dilemma" to explain why an advanced technological civilization may destroy itself if it is premature, describing this dilemma as due to the "interaction between technology and politics that favors the uneven growth of the technologies of self-destruction relative to the political capacity to control and restrain them."

3.2 Entering the Growth Spiral

The comparison with cancer can be taken further. The Industrial Revolution, which triggered an economic growth explosion, is mirrored in cancer, where cells enter a growth spiral (akin to the feedback loop in growth discussed in the previous section). This is because, once the k steps are cleared, the cell begins to double.The number of cells C at time t after the final mutation (at say $k = 7$) is:

$$C(t) = C_0 \cdot e^{rt} \tag{10}$$

Where r is the growth rate.

If it is assumed that the last hard step required for the Industrial Revolution was in place around 1700, and that the growth explosion could then be reflected in data from around 1750, then the following linearised version of equation (10) can be estimated, to derive estimates for the GDP growth rate between the year 1750 (C_o/β_0) and 2023:

$$\ln(C(t)) = \beta_0 + \beta_1 t + \epsilon \tag{11}$$

where $C_0 = \beta_o$ and $r = \beta_1$, and adding an error term (ϵ),

Because world GDP data, as shown in Figure 1, is non-stationary, a regression on non-stationary levels risks a spurious regression. An Augmented Dickey-Fuller (ADF) test confirmed that in the present case, this holds. Hence, equation (11) was estimated using the growth rate of world GDP (calculated as first differences of the logs) rather than the levels.

Taking the first difference of the log-linear equation $\ln(C_t) = \beta_0 + \beta_1 t + \epsilon_t$, the time variable t becomes a constant, and β_1 becomes the intercept of the new equation. The specification for the growth rate is:

$$\Delta \ln(C_t) = \beta_1 + u_t \tag{12}$$

Where:

$\Delta \ln(C_t)$ is the annual growth rate in world GDP (log-difference); β_1 is the average annual growth rate; and u_t is the error term.

Due to high autocorrelation in GDP over time, the standard OLS assumption that the error terms are independent will be violated. To address this it is appropriate to use Newey-West Standard Errors, which are robust to both heteroscedasticity and autocorrelation. In the present case this was done using the Greene formula ($T^{1/4}$) to determine the number of lags to include. In this case, for 273 years, it is 4 lags.

The regression results are contained in Table 2.

Table 2: Regression results, dependent variable growth rate in World GDP, 1750 - 2023

Variable	Coefficient	Newey-West std. err.	t	P>$\|t\|$
β_1	0.0184	0.0018	10.42	0.00
N=273				

The estimate of β_1 contained in Table 2 indicates that, on average, the world economy grew by approximately 1.84% per year between 1750 and 2023. Plugging this value into the Rule of 70 gives:

$$\text{Years to Double} = \frac{70}{1.84} \approx \mathbf{38} \text{ years}$$

At a steady growth rate of 1.84%, the size of the world economy doubled roughly every 38 years since 1750.

3.3 Reaching the Lethal Burden

In the case of cancer, the collapse of the organism can occur when $C(t)$ reaches what is known as the “Lethal Burden.” According to Pienta et al. (2025, p.184) “It is widely accepted that a total tumour burden of 1 kilogram within a patient is lethal.” While this is a relatively small percentage of say an adult's total body mass, the lethality of the tumour occurs when this burden triggers tipping points - when it "affects the body as a whole (systemic effects)" (Pienta et al., 2025, p.184). These systemic effects may, for instance, trigger a tipping point, when a tumour consumes more glucose and oxygen than the host can provide, or interferes with organ function.

Humanity may be compared to a cell that just cleared its k^{th} mutation, in the case of humans, the k^{th} hard step to initiate the Industrial Revolution. Since around 1700, humanity has been in the e^{rt} phase as per equation (2). Rees (2020) calls this humanity's "plague phase." According to Rees (2020, p.5) "Some species in simple ecosystems exhibit regular cycles of outbreak followed by collapse in which the outbreak is referred to as the 'plague phase' of the cycle [...]The plague continues until negative feedback—food shortages, disease, predation, etc., depending on species and circumstances—knocks the population back."

During humanity's "plague phase", it devours non-renewable resources - specifically, resources that had taken the Earth's systems billions of years to create. If r (GDP growth) continues, the size of the world economy will eventually reach a *Lethal Burden* in terms of the Earth's carrying capacity, and trigger various tipping points in the Earth System. Estimates suggest that the size of the global economy is already far beyond Earth's carrying capacity. According to Malmaeus et al. (2025, p.9), the world's total material footprint needs to be reduced from over 90 billion tonnes to 50 billion tonnes per year in order to be compatible with the planet's ecology.'

In section 4.2 below, the extent and danger of the current ecological overshoot of the Earth's carrying capacity are discussed in more detail.

3.4 Collapse

Just as a tumour eventually enters a growth spiral that consumes the host's resources, economic growth is driven by a positive feedback loop between capital accumulation and extraction. For most of human history before the Industrial Revolution, the global economy had a doubling time of approximately 6,000 years.[7] The world's pre-Industrial Revolution state can be compared to the "pre-cancerous" state of an organism, where the Hard Steps (mutations) are so difficult to clear that growth is effectively stagnant. Much like a cell with strong tumour-suppressor genes, pre-industrial human societies may have had growth-suppressor constraints, such as limited energy sources, slow communication, autocratic governance, and superstitious beliefs.

Since the Industrial Revolution, the doubling time of the global economy has decreased from 6,000 years to roughly 38 years, as shown above. In the Nunney (2020) and Nordling (1953) models, cancer occurs when a cell's internal checks fail, allowing it to extract resources from the host at an ever-accelerating rate. Modern GDP growth functions similarly, with society and its corporations using technology to extract energy and resources with increasing efficiency.

How long can economic growth continue at its current rate before hitting the lethal limit and triggering a collapse in GDP and population? How much time does humanity and current civilization have left?

4 How Much Time Does Humanity Have Left?

The analysis in the previous section suggests that an exceptional outcome, such as the Industrial Revolution, which required multiple hard steps, is most likely to occur, if at all,

[7]Source: See https://www.bankofengland.co.uk/explainers/how-has-growth-changed-over-time

towards the end of humanity's existence, rather than at the beginning.

This means that, given the Industrial Revolution, the answer to the question is: how much time does humanity have left? - Is that its time is short: humanity is in its end-phase.

In the rest of this section, an attempt will be made to provide a more precise estimate of the time left for humanity as a species and for economic growth to continue. Four arguments or points of view will be set out: a philosophical argument (the Doomsday Argument), an astrobiological argument (The Great Filter), a physics argument (Thermodynamic Limits), and empirically based predictions.

4.1 The Doomsday Argument

The Doomsday argument is a probabilistic prediction of humanity's remaining lifespan. It draws on Bayesian reasoning. It estimates the probability of the total number of humans who will ever live (N) based on the birth rank (n) of the current generation, in other words, on the number of humans who have ever lived.The argument is attributed to Carter (1983), Leslie (1996) and Gott (1993). A primer is provided by Bostrom (2023).

If one assumes the Copernican Principle - in other words, assuming that the current generation is not in the position of a privileged observer (Gott, 1993), and hence likely a typical generation—then its "birth rank" n in terms of how far into the existence of humanity it exists, provides an indication about the total size of N. Formulated in terms of Bayes' Rule[8], this can be calculated as:

[8]Bayes's Rule "allow us to extract precise information from vague data, to find narrow solutions from a huge universe of possibilities. They were central to how British mathematician Alan Turing cracked the German Engima code. This hastened the allied victory in World War II by at least two years and thus saved millions of lives" (Lee and King, 2017).

$$P(H|E) = \frac{P(E|H) \cdot P(H)}{P(E)} \tag{13}$$

Where H is the prediction - e.g. that humanity ends soon - and E is the evidence - e.g. the current birth rank, (n) of the observer.

It can be assumed that there is a 50/50 chance that humanity has passed the midpoint of human history. Why is this the case? The answer is that more humans are alive today than at any point in the past 300,000 years. If anyone currently alive is a random human, they are more likely to be born when the population is at its peak.

To estimate the median (50%) expectation of the total number of humans who will ever live $(P(N_{total} \leq X))$, based on the current birth rank of human observers,(n), the calculation of the point where the cumulative probability reaches 0.5 is :

$$P(N_{total} \leq X|n) = 1 - \frac{n}{X} = 0.5$$

Solving for X:

$$\frac{n}{X} = 0.5 \implies X = 2n$$

As of 2022, it is estimated that approximately 117 billion humans have ever lived.[9] This means the birth rank ($n = 117$ billion). Given that the current global birth rate is approximately 134 million births per year[10] then the time remaining for humanity is:

$$\frac{117,000,000,000 \text{ humans}}{134,000,000 \text{ humans/year}} \approx \mathbf{873} \text{ years}$$

[9]This figure is obtained from the Population Reference Bureau (PRB), see `https://www.prb.org/articles/how-many-people-have-ever-lived-on-earth/`

[10]See UN's World Population Prospects, at `https://population.un.org/wpp/`

Thus, there is a 50% chance that humanity will end within the next **900 years** - meeting Doomsday[11] around the year 2900 AD.

One may point out that the current birth rate of 134,000 people per year is declining, and therefore one should not assume that this will remain constant. If the number of births per year decline, then the "budget" of 117 billion future humans will be utilized over a longer period.

According to Basten et al. (2013, p.1146) if global total fertility rate (TFR) converge to the current European TFR (≈ 1.5), then the global population will "decline to 2.3-2.9 billion by 2200." Too see the implications for the Doomsday date, and taking Basten et al. (2013)'s upper estimate of 2.9 billion people as the total global population by 2200, then with a shrinking society only approximately 12.5 billion people will be born between 2026 and 2200, leaving 104.5 billion people remaining to live. As by 2200 there would be only 31.9 million births per year, and if humanity by then manages to stabilize the population at 2.9 billion, then the 117 billionth future human would be born around in **3500** years - around the year 5475.

The calculations in the previous paragraph imply that under the Doomsday Argument, a relatively sharp population decline actually delays the end of humanity. If for instance, humanity aims to survive for another 10,000 years, the birth rate need to decline to approximately 12 million births per year, consistent with a global population of around 1 billion people - not much more than the world population total roughly at the start of the Industrial Revolution.

Interestingly, Daily et al. (1994, p.474) estimated that the optimum world population size, taking into account ecological pressures and human needs, lies not too far from this Dooms-

[11]For a critical discussion of the Doomsday Argument see e.g. Olum (2000) who argues that one should not only consider one's position in the birth order of a species, but also consider the fact that one exist at all, as being more probable in a longer-lived rather than a shorter-lived species.

day argument-based estimate, "in the vicinity of 1.5 to 2 billion people." They reckon that this number, "if achieved reasonably soon, would also likely permit the maximum number of Homo sapiens to live a good life over the long run."

For the present generation, a time-frame of anything from 900 to 3500 years may seem like there is still much time left; however, against the total time humans have so far existed, 900 years is but 0.3%. If humanity's tenure on Earth were compared to an individual who lives to 100 years, humanity would already be 99 years and 8 months old.

As Bostrom (2023) remarked, when reading such a forecast, "*Nearly everybody's first reaction is that there must be something wrong with such an argument. Yet despite being subjected to intense scrutiny by a growing number of philosophers, no simple flaw in the argument has been identified.*"

4.2 The Great Filter

The Great Filter links the Hard Step model of Carter (1983, 2007) with the Fermi Paradox. The Fermi Paradox, or more accurately, Fermi's Question, is the question the physicist Enrico Fermi asked in 1950: "*Where is everyone?*" referring to the absence of any sign of alien intelligence in the universe despite the age of the universe and the abundance of planets[12] (Cirkovic, 2018; Gray, 2015; Hart, 1975).

Applying the Hard Steps Model suggests that the reason there is no evidence of any other technologically advanced civilizations in the universe may be because the odds of a planet clearing all k hard steps are very low. It suggests, in particular, that there is no evidence of such civilizations, because they likely do not survive to spread through the galaxy - to become space-faring and/or able to leave noticeable techno-signatures. This means there is

[12] And the fact that the Earth itself is a "latecomer" among planets: the "median age of terrestrial planets is 1.8 ± 0.9 billion years older than the age of the Earth" (Armstrong and Sandberg, 2013, p.1)

a Great Filter that eliminates technologically advanced civilizations from surviving for long enough. Technological civilizations may be very short-lived affairs.

The idea of a Great Filter was proposed by Hanson (1998). According to Hanson (1998) the probability of a planet producing a space-faring civilization (P_{civ}) is the product of the probabilities of every individual hard step (k_i):

$$P_{civ} = \prod_{i=1}^{n} k_i = k_1 \times k_2 \times k_3 ... \times k_n$$

As was discussed in section 2.1, it is estimated that there have been 6 hard steps that had to be passed before a complex human technological civilization emerged, and that that civilization has passed through 6 hard steps to the Industrial Revolution, after which GDP growth "exploded."

If the probability of any one step for a planetary civilization is 10^{-9} (one in a billion), the chances of a planet reaching the next step, step 7, and becoming space-faring and/or able to leave noticeable techno-signatures, are incredibly small.

The *Hard Steps Model* suggests that for human civilization to exist long enough to overcome the final Hard Step to being space-faring and/or able to leave noticeable and lasting techno-signatures, it has to avoid a Great Filter.

There are several candidates for the Great Filter. These include self-induced and natural risks that can eradicate a technological civilization. Self-induced risks include triggering an ecological disaster, as discussed in section 3.3. Kemp et al. (2022) sets out the reasons why climate change constitutes an existential risk.

Another self-induced risk is a nuclear conflict. Game-theoretic considerations suggest that, as long as the probability of nuclear weapon use is non-zero, the long-term survival probability $P(s)$ of humanity approaches zero over time (Ord, 2020). This is an important result, especially in light of the fact that "The last remaining treaty between the United States and Russia limiting nuclear weapons expired on February 5, 2026. It marks the end of an era of arms control and limits on both the size and status of U.S. and Russian nuclear weapons" (Dumbacher, 2026).

The essence of this result can be seen if one defines p as the probability of a nuclear exchange in any given year ($0 < p < 1$), with $P(s_t)$ = the probability that humanity survives a single year t. From this, the probability of survival over T years is simply $P(s_t) = 1 - p.P(S_T)$.

In a repeated game, where the probability p is independent each year, the survival probability over T years is:

$$P(S_T) = (1-p)^T$$

As T approaches infinity ($T \to \infty$), and because $(1-p)$ is less than 1, it is the case that $\lim_{T\to\infty}(1-p)^T = 0$, i.e. $P(S_T) \to 0$.

Some have argued that the creation of AI - that may become an Artificial Superintelligence (ASI) - is another self-induced existential risk (Bostrom, 2014). If such an ASI can be developed, and if it can substitute for human labor, in effect making human labor accumulable just like physical capital (Almeida et al., 2024), then, in terms of the Galor (2011) model summarised in section 2.3, the new production function for ideas becomes:

$$g_{A,t+1} = \phi(e_t, L_t, S_t) \tag{14}$$

Where S_t denotes the ASI. Because AI models can be replicated instantly, there is no biological waiting time as in "growing" human capital : S_t can design S_{t+1}, so that the growth rate of technological innovation (g_A) shifts from following a power law (t^k) to become hyper-exponential. In such a shift, economic growth (g_y) becomes dependent on the quantity of compute rather than on the quality of human capital. This can compress the doubling time of GDP from 38 years to a very much shorter time (Almeida et al., 2024; Jones, 2022).

In addition to self-induced Great Filters such as Artificial Intelligence, there remain natural risks, including pandemics and meteor impacts, which pose existential risks. For a discussion of these, see Ord (2020).

If the Great Filter at hard step $k = 7$ is a recurring cycle of societal collapse due to resource depletion or climate change, human civilization may collapse without human society going extinct, but remaining in a new era of Malthusian Stagnation - not wealthy or stable enough to pay the energy tax required to leave the planet's gravity well.

The Great Silence may thus be the result of the galaxy being a graveyard of civilizations that either never reached their own Industrial Revolutions, or soon after reaching it, collapsed and/or went extinct.

To narrow down the likely time left for humanity to overcome the last hard step, $k = 7$, one can again resort to Bayesian thinking.

According to Gott (1993), if the current generation of humanity is not special (Copernican principle), they are probably not living at the beginning or the very end of humanity. According to Gott (1993), the current observation time (t_{now}) is a random point in the total lifespan of human industrial society (T_{total}), which begins at t_{begin} and ends at t_{end}.

Letting t_{past} be the time industrial civilization has already existed ($t_{now} - t_{begin}$) and t_{future} be the time remaining ($t_{end} - t_{now}$). If the current generation is at a random point in time, there is a 95% probability that it is located somewhere in the middle 95% of the total timeline - not in the first 2.5% or the last 2.5% (Olum, 2000)

At the earliest possible random point (2.5%), only 1/40th of the time has passed, and 39/40ths remain. In this case, t_{future} is 39 times as long as t_{past}. At the latest possible random point (97.5%) 39/40ths of the time have passed, and only 1/40th remains. In this case, t_{future} is 1/39th of t_{past}.

Hence, the formula for the 95% confidence interval is (see Olum (2000, p.3)):

$$\frac{1}{39}t_{past} < t_{future} < 39t_{past} \tag{15}$$

Given that the Industrial Revolution started roughly in 1700 - around 326 years ago - one can set $t_{past} \approx 326$ years. In this case the consideration is specifically about the start of the Industrial Revolution. In the context of the Great Filter, and the duration of economic growth, this is the most critical calculation.

From equation (9) the lower bound is (t_{min}):

$$t_{min} = \frac{326}{39} = \textbf{8.4} \text{ years}$$

and the upper bound (t_{max}):

$$t_{max} = 326 \times 39 = \textbf{12,714} \text{ years}$$

There is thus, based on this reasoning, a 95% probability that the current industrial-technological civilization will last between 8 years and 13,000 years.[13]

The Copernican Principle logic underlying this result is that the end is likely closer than further away in the future, because if the end were, say, 1,000,000 years away, it would be highly improbable for a current human to find themselves in the first 0.025% of that history.

The calculations from equation (9) provide a mathematical solution to Fermi's Question. It suggests that the hard step $k = 7$ is an extremely narrow window. If civilizations only stay

[13] Gott (1993) using t_{past} as 200,000 years found a maximum duration of 7,8 million years. This did not account for the Industrial Revolution. The IR severely constrains the longevity of the human species.

technological for an average of $\approx$ 6,500 years (the midpoint of the 13,000-year upper bound), then even if the galaxy contains many technological civilizations, very few civilizations are likely to exist at the same time. It also reflects the relevance of a likely energy trap: 6,500 years may not be enough time to develop the physics and energy required for interstellar colonization.

4.3 Thermodynamic Limits to Growth

Another point of view from which to examine the question of how long global GDP growth can continue at its current pace (around 1.8% p.a.) before the size of the economy hits a "lethal" burden, is that of thermodynamics. Economic growth requires energy. And all energy use eventually ends up as waste heat (Second Law of Thermodynamics). At some point this waste heat becomes a lethal burden.

4.3.1 Boiling the Oceans

The argument in this section comes from physicist Tom Murphy's *Nature Physics* paper on the limits to growth, see Murphy (2022).

The total incoming solar flux that Earth receives from the Sun is $174,000$ TW every second (1 W = 1 Joule/second). Of this, around 30% is reflected back into space, leaving Earth to absorb around 121,500 TW. In comparison, the global economy (P_0) uses approximately 1.8×10^{13} Watts (18 TW) of energy in a year. The Earth receives more energy from the Sun in one hour than the entire world economy uses in a full year (Nussey, 2019).

This 18 TW energy use nevertheless causes an Anthropogenic Heat Flux (AHF),(q_h). Currently this is roughly 0.03 W/m^2 given that the Earth's Surface Area (A) is 5.1×10^{14} m^2. While measurable, it is clearly still small - around 30 times smaller than the warming caused by CO_2 emissions. The historical annual growth of energy consumption(r) has been $2.3\% = 0.023$ (Murphy, 2022).

With this information, the amount of energy used after 400 years, can be calculated using the formula for exponential growth:

$$P(t) = P_0 \cdot (1 + r)^t \tag{16}$$

For $t = 400$, $P_0 = 18Tw$, and $1 + r = 1.023$, after 400 years total energy consumed will have grown to $P(400) \approx 160,519$ TW. In other words, the world is using $160,519 \times 10^{12}$ Joules every second. In 400 years, human energy use would hence exceed the total solar energy absorbed by the entire planet of 121,500 TW.

How much warming will this cause?

The world's current average temperature (T_0)is around 15°C, or $288.15K$ (Kelvin). Let the future temperature after continued economic and energy growth be (T_{final}). This can be estimated using the Stefan-Boltzmann law, in terms of which the absolute temperature T of a body is proportional to the fourth root of the energy flux F it must radiate away ($F \propto T^4$).

Thus, the ratio of the new temperature to the old temperature is:

$$\frac{T_{\text{new}}}{T_{\text{now}}} = \left(\frac{P_{\text{total}}}{P_{\text{solar}}}\right)^{1/4}$$

Where $P_{\text{total}} = P_{\text{solar}} + P_{\text{waste}}$.

After 400 years:

$$T_{\text{new}} = 288.15 \text{ K} \times \left(\frac{121,500 \text{ TW} + 160,974 \text{ TW}}{121,500 \text{ TW}}\right)^{1/4}$$

$$= 288.15 \text{ K} \times 1.2348 \approx 355.8 \text{ K}$$

In terms of degrees Celsius this is

$$355.8 \text{ K} - 273.15 = \mathbf{82.65}°\text{C}$$

The exact year when the exact year (t) when T_{new}= 100°C can be calculated using (16). This is in ≈ **414** years.

Continued growth in energy consumption on planet Earth, even if the energy consumption is 100% decarbonized, is not possible.

4.3.2 The Existential Danger of an Artificial Superintelligence

With GDP doubling being compressed by the successful development of an ASI, which accelerates growth (see the discussion in the previous section), the global economy will hit the Lethal Burden of boiling oceans much sooner.

To see how much sooner, and why hopes of accelerating GDP growth through AI may be misplaced, recall that total current global power (P_0) consumption is ≈ 18 TW.

Using the Stefan-Boltzmann Law, and plugging in the world's current average temperature of 15°C (288.15 K), and the boiling temperature of the oceans, 100°C (373.15 K), the required increase in total power is given by :

$$\left(\frac{T_{new}}{T_{old}}\right)^4 = \left(\frac{373.15}{288.15}\right)^4 \approx 2.812$$

Since, as already noted, the Earth absorbs approximately 121,500 TW of solar energy, to boil the oceans, the total power must increase by 2.812 times to $\approx 341,665$ TW. This means that $341,665$ TW $- 121,500$ TW $= \mathbf{220,165}$ TW waste heat needs to be generated from economic growth. If an ASI raises annual GDP growth to 35%, and assuming a 0.9 correlation with energy growth, energy consumption grows at rate (r):

$$r = 0.35 \times 0.9 = 0.35 \text{ (or 35\% per year)}$$

Using the exponential growth formula $P(t) = P_0 \cdot e^{rt}$, the number of years for this growth to boil this oceans can be calculated as t (years):

$$220,165 \text{ TW} = 18 \text{ TW} \cdot e^{0.315 \cdot t}$$

From which solving for t gives :

$$t = \frac{9.4117}{0.35} \approx \mathbf{26} \text{ years}$$

Thus, if GDP growth accelerates to 35% per year, and remains tied to energy use, hit would boil the Earth's oceans in approximately **26 years**.

Tech optimists may now argue that AI will become more efficient, using less energy. However, physics imposes the *Landauer Limit.* As explained by Bormashenko (2025, p.1), Landauer's principle "sets a limit on the minimum energy necessary for the erasure of one bit of information" with "the minimum amount of heat/energy dissipated when erasing one bit of information" described by

$$E = k_B T \ln 2$$

Where k_B is the Boltzmann constant (1.38×10^{-23} J/K) and T is the absolute temperature in Kelvin, with $\ln 2$ representing the change from two possible states (0 or 1) to one.

At room temperature (25°C or 298 K), this limit is approximately 2.9×10^{-21} Joules. Although current AI energy consumption is far from this limit, even if, by some stroke of ingenious innovation, AI technology achieves perfect efficiency, if the number of operations doubles every 2 years, energy consumption must eventually follow, regardless of efficiency gains.

The upshot is that in the case of successful ASI development and explosive AI-driven GDP growth, the Lethal Burden is reached in approximately **30** years after the invention of this ASI. According to the AI 2027 project, this invention may be imminent, stating[14] "By 2027, we may automate AI R&D leading to vastly superhuman AIs ('artificial superintelligence' or ASI). In AI 2027, AI companies create expert-human-level AI systems in early 2027, which automate AI research, leading to ASI by the end of 2027."

Long before the technical lethal limit is reached, the Earth would likely become too hot for humans to survive. The *Human Climate Niche* is very narrow: human society has peak population densities at local climates with a mean annual temperature (MAT) of ≈ 13 °C and a secondary peak at ≈ 27 °C (Lenton et al., 2023). The so-called 35°C wet bulb temperature (Tw) "represents a thermodynamic limit to heat exchange, whereby the human body becomes an adiabatic system" - meaning death after 6 hours of exposure (Vanos, 2023, p.1).

Of course, the assumption that human society can continue to experience "clean" GDP growth of 1.8% per annum, with its 99% correlation with energy growth, for very long is a heroic one. If it continues and all fossil fuels are exploited, it will release at least 5 trillion tons more carbon, resulting in atmospheric CO_2 levels skyrocketing from their current 425 ppm to around 2,000 ppm (Tokarska et al., 2016). This could cause an increase in average

[14] See `https://ai-2027.com/summary`

global temperature of between 4°C and 10°C, with carbon levels comparable to those that triggered the Permian-Triassic extinction event 252 million years ago.

Assuming that the green growth advocates are correct in their optimism that a full transition to 100% renewable energy is possible, then with 100% renewables, a roughly 1.8% GDP/energy growth will, in 250 / 300 years, require solar panels on every square meter of land on the planet (Murphy, 2021). This seems rather unfeasible.

In conclusion, as Murphy (2021, p.13) warns,

> "In the end, physics puts a timeline on expectations with respect to growth in energy on Earth. Maybe the $\approx$ 300 year scale is not alarming enough. But it imposes a hard barrier against preserving our historical growth rate. In reality, other practicalities are likely to assert themselves before these hard limits are reached. We can therefore expect our growth phase to end well within a few hundred years. Given that the growth phase has lasted for far longer than that, we can say that we are closer to the end of the saga than to the beginning."

Thus, thermodynamic limits suggest at most a "few hundred years", say **200 - 300 years** of GDP growth, and even as short as **26 years** after the invention of an ASI, before human civilization may end.

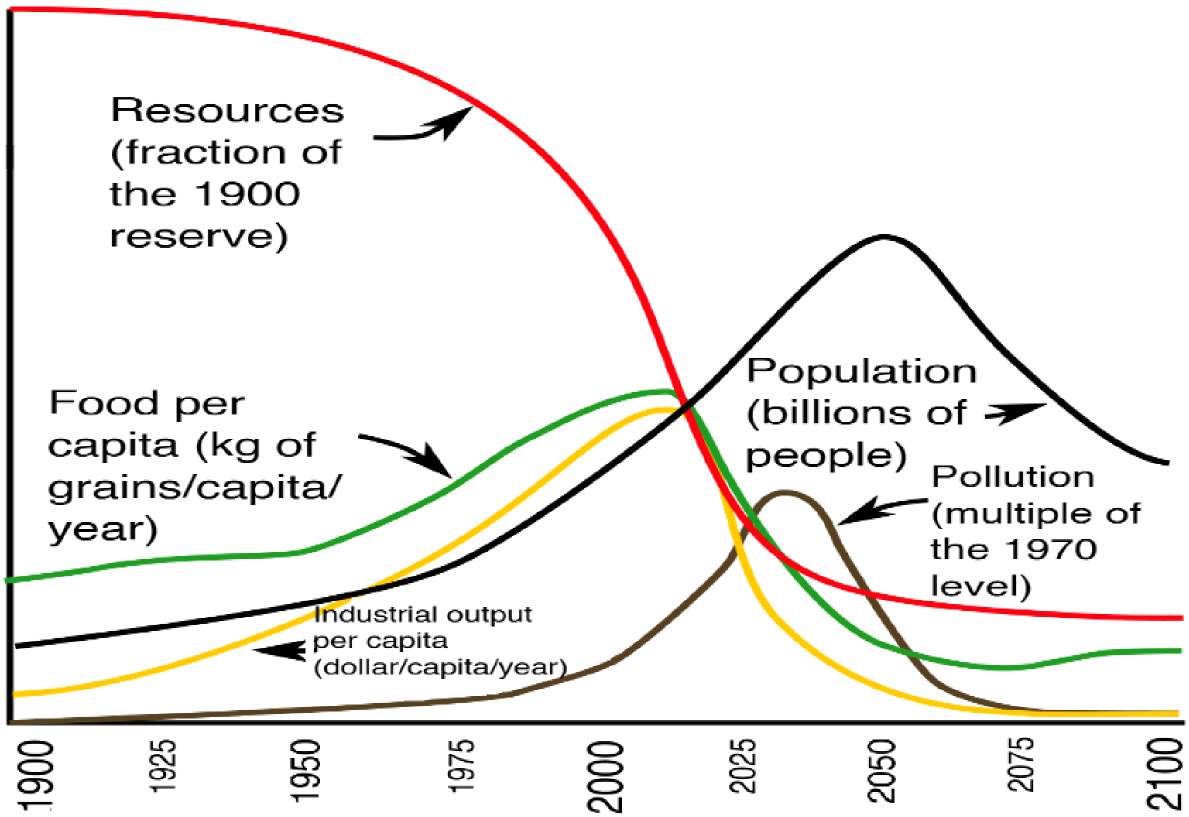
4.4 Empirical Predictions

4.4.1 The Limits to Growth Study

The first mathematical, computer-based simulation model to study societal collapse was the *World3 Model*, used to generate predictions for the 1972 Club of Rome's *Limits to Growth* (LtG) study (Meadows et al., 1972).

The study produced various graphs of future growth, which tend to reflect the same power-law dynamics (see Figure 3). As shown in Figure 3, the predictions were that industrial output and food production would peak between 2000 and 2025, and that pollution and population would also peak shortly thereafter.

Figure 3: Predictions under the Business as Usual Scenario, Limits to Growth Report, 1972



Source: Wikipedia, CC BY-SA 4.0

This study concluded (p.23) that

> "If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years."

Thus, the LtG study predicted that economic growth would collapse before 2072 - i.e. in the next **40 years** or so.

Recent updates to the LtG study by Turner (2014) and Herrington (2021) confirmed that the global economy continued to track the standard-run scenario well. Hence, according to Turner (2014), "*it would appear that the global economy and population are on the cusp of collapse*."

4.4.2 Fertility Decline

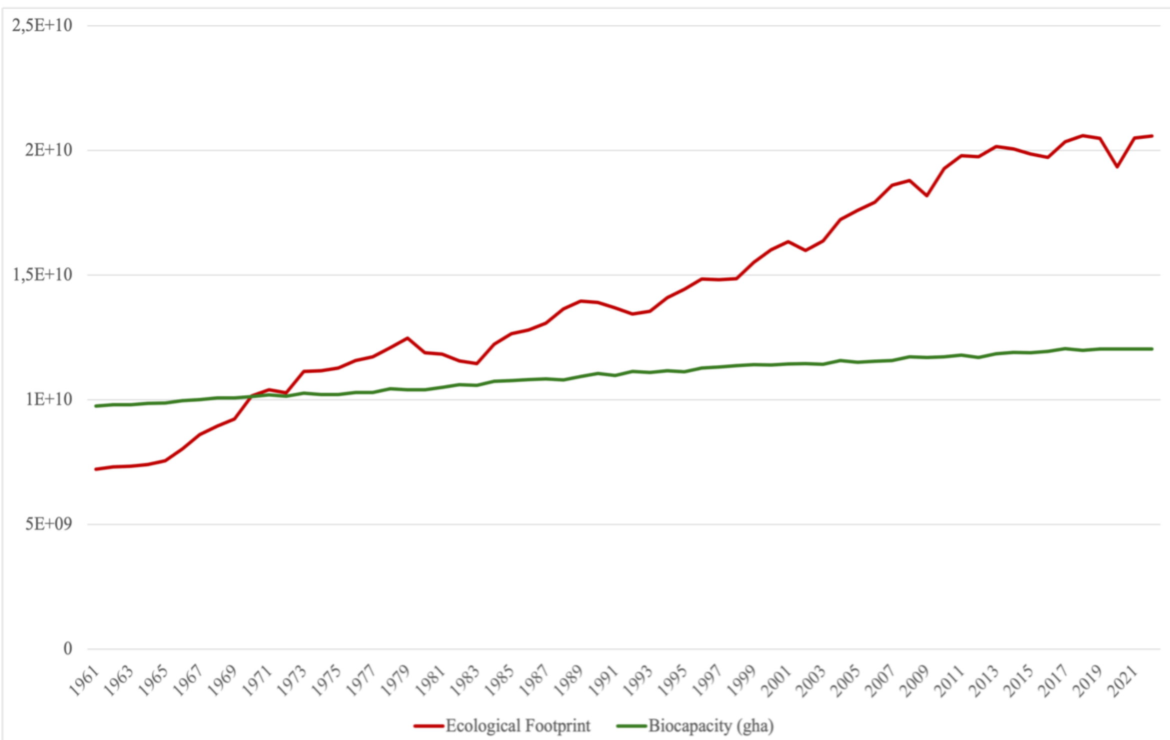
More recent empirical evidence that places a near-term limit on humanity's economic and population growth was provided by Zliobaite et al. (2017). They used fossil data from large herbivorous mammals and marine life covering the last 40 million years in the USA and Mexico, 22 million years in Europe, and 7 million years in Africa. Applying fossil data analysis, stochastic modelling, and statistical benchmarking, they explored the "hat-like" pattern followed by most taxa in their sample. This hat-like pattern refers to the empirical observation that taxa typically evolve to have a single, clearly expressed peak between their emergence and extinction. The peak of a taxon is the point of maximum expansion.

Zliobaite et al. (2017) found that the expansion phase in the lifetime of a taxon, such as mammals, is primarily driven by biotic factors, such as competition for resources. After reaching a peak, taxa then typically begin a waning phase. Zliobaite et al. (2017) note that while competition drives the prime of a taxon, abiotic factors - i.e. environmental change- become the dominant force as a taxon approaches extinction.

In the present context, the implication is that, for humans, the Industrial Revolution triggered the expansion of humanity at an unprecedented rate, which has now pushed it toward a peak in occupancy. According to Zliobaite et al. (2017), humanity has reached this peak after a biotic struggle (competition), but its failure (potential extinction) will likely be determined by humanity's inability to withstand the abiotic environmental changes that typically dominate the final phase of a taxon's existence.

The peak that a taxon reaches in its findings is when it reaches its carrying capacity. At this peak, competition intensifies as resources become scarcer. The decline toward extinction begins when the environment changes in a way that causes this carrying capacity to decay, so that the environment can no longer support the taxon at its peak levels. Indications are that this is the situation facing humanity at present. One such indication is that humanity has exceeded Earth's carrying capacity. A measure of this is given by the *Ecological Footprint* of humanity (Borucke et al., 2013; Wackernagel and Beyers, 2019). Figure 4 shows humanity's Ecological Footprint relative to available bio-capacity, measured in global hectares (gha), from 1961 to 2022.

Figure 4: Humanity Exceeding Ecological Carrying Capacity, 1961-2022



Source: Author's compilation based on data from the Global Footprint Network: https://data.footprintnetwork.org/)

Figure 4 shows that the world has exceeded its bio-capacity already in the 1970s.

According to the Global Footprint Network,[15]

[15] See https://www.footprintnetwork.org/what-ecological-footprints-measure/

> "*Humanity demands goods and services from nature that require 20.8 billion global hectares to renew them, as of 2023. This is more than the 12.2 billion global hectares of biologically productive area (or bio-capacity) available on the planet. Excessive demand means that humanity, by now, uses 1.7 times more than the amount the biosphere currently renews. Some describe this level of consumption as using 1.7 Earths.*"

A second indication that that the environment can no longer support the human taxon at its peak levels is that human fertility rates are declining. According to Bardi (2026) this is likely partly due to "chemical pollution. Plenty of evidence points to human-made chemicals causing havoc to the human reproductive system, both in males and females."

Given that humanity is consuming far above the carrying capacity of the planet, as a result of the Industrial Revolution and its consequent economic growth explosion, and that fertility rates are falling as a result of chemical pollution, the survival of a humanity can be modeled by the net change in population (ΔP) relative to the carrying capacity (K) and the population fertility rate (r):

$$\Delta P = \frac{dP}{dt} = rP\left(1 - \frac{P}{K}\right) \tag{17}$$

The Ecological Overshoot, shown in Figure 4, means that per equation (17) that humans have artificially inflated P (population) through capital- and technology-driven super-extraction K (resources like fossil fuels and groundwater).

It is clear that once K is exhausted, the term $(1 - P/K)$ becomes negative (which Figure 4 suggests is the case). Moreover, Gee (2025) argues that for humans, r is becoming negative at the same time that K (carrying capacity) is shrinking.

Why would r become negative? One reason, explored by Gee (2025) and Levine et al. (2017), is the current decline in male fertility. If $S_0 = 99$ million/mL is the average Western sperm count in 1973, and r is the rate of decline ($\approx 1.2\%$) (Levine et al., 2017), then applying the by now familiar growth formula:

$$S(t) = S_0 \cdot e^{-0.012t}$$

then by the year 2130 (in **104 years** from the time of writing) average sperm counts will have fallen to 15 million/mL - which the WHO considers as so low that natural reproduction becomes statistically unlikely without medical assistance.

While mammalian species typically last about a million years (Gee, 2025; Ord, 2020), and while Gott (1993)'s Doomsday Argument calculations, without controlling for the Industrial Revolution estimated a duration for humanity of up to 7.8 million years, due to the Industrial Revolution humanity's existence will likely be shortened to not much more than a third of this, $\approx 300,000$ years.

5 Simulated Late Stage Capitalism

The Industrial Revolution, as the beginning of the end of humanity, can now be seen, in light of the foregoing discussion, as an explanation to the Fermi Paradox, or Fermi's Question, "*where are they*?" in relation to other technologically advanced life in the universe. The answer is that there is a Great Filter that truncates such life before it can spread and produce lasting techno-signatures. The Industrial Revolution is such a Great Filter - leading, cancer-like, to growth in the consumption of the species that overwhelms its planetary systems.

There is, however, a different, even more speculative possibility that may answer the Fermi Question. This is that human civilisation is a simulation.

That Simulation Hypothesis has been proposed by Bostrom (2003). According to Bostrom (2003, p.6) "Posthuman civilizations would have enough computing power to run hugely many ancestor-simulations[16] even while using only a tiny fraction of their resources for that purpose." He comes to this conclusion by calculating that a computer that can perform 1042 operations per second, based only on known nanotechnology, "could simulate the entire mental history of humankind (call this an ancestor-simulation) by using less than one millionth of its processing power for one second" (Bostrom, 2003, p.6).

Based on this point of departure, that such ancestor-simulations will be possible in the future, Bostrom (2003, p.7) then calculates the fraction of all observers with human-type experiences who live in simulations (f_{sim}) based on probabilistic reasoning:

$$f_{sim} = \frac{f_P f_I \overline{N_I}}{(f_P f_I \overline{N_I}) + 1} \tag{18}$$

Where f_P is the fraction of civilizations that achieve the ability to run an ancestor-simulation; f_I is the fraction of civilizations that are interested in running simulations; and $\overline{N_I}$ is the average number of ancestor-simulations run by interested civilizations.

Since $\overline{N_I}$ is "extremely large" - "because of the immense computing power of post-human civilizations" (Bostrom, 2003, p.7) - the denominator is dominated by the left term unless f_P or f_I are nearly zero. This leads to the conclusion that either civilizations go extinct ($f_P \approx 0$) - i.e. there is a Great Filter that cannot be avoided - they lose interest in simulations ($f_I \approx 0$), or reality is almost certainly simulated ($f_{sim} \approx 1$) given the size of $\overline{N_I}$.

Equation (18) seem to "condemn us to a pessimistic vision of the world where we are either prisoner of someone else's simulation (and thus at their mercy), or on a path towards assured self-destruction" (Bibeau-Delisle and Brassard, 2021, p.4).

[16] Simulating all of human history (approx. 117 billion lives) would require roughly 10^{33} to 10^{36} operations (Bostrom, 2003).

If it is the former, an interesting question arises: why would any very advanced technological civilization that can run ancestor-simulations, specifically want to simulate the Industrial Revolution and growth take-off period?

Answers to this question can only be highly speculative, but may nevertheless cast light on the current human predicament. The current period seems to be the only period in humanity's 300,000-year history where it may either clear the final hard step(s) towards Galactic expansion, or succumb to the Great Filter. In effect, the Simulation may be a simulation of late-stage capitalism. In such a simulation, the economic growth spiral can be the central mechanic being studied to test whether any civilization can survive its own economic growth metastasis.

Once the simulation is over, it may simply be switched off.

6 Concluding Remarks

Conventional wisdom has it that the Industrial Revolution was the moment humanity broke free from the shackles of Malthusian stagnation through ingenuity and innovation. It is essentially narrated as a story of a beginning - how humanity found the way to a prosperous future.

This paper applied the Hard Steps model — a framework borrowed from evolutionary biology and astrophysics — to reconstruct the Industrial Revolution not as a dawn, but as the beginning of the end-phase of humanity. Analogous to the incidence of cancer, human civilization has for millennia had growth-suppressors — limited energy, small-scale communications, and non-extractive institutions - that kept its material footprint in a thermodynamic equilibrium. It took at least six hard steps for modern humans to overcome these, a slow process unfolding over 300,000 years, but eventually culminating around 1700 in the Industrial Revolution.

Just as a tumour eventually creates a lethal burden that kills its host, the world economy's post-1700s economic growth—doubling every 38 years - has entered a runaway exponential spiral. This hockey stick trajectory mimics the final, fatal expansion of a cancer cell. While mammalian species typically live for one million years, for humans, the Industrial Revolution has significantly reduced this lifespan.

Mainstream economists tend to assume that innovation will come to the rescue; however, this paper presented conclusions from thermodynamics which showed that if all growth is driven by 100% clean, renewable energy, the waste heat generated by continued 1.8% economic growth (which implies similar growth in energy consumed) would boil the Earth's oceans in 400 years. Even AI will not save humanity: if a superintelligence is invented and it succeeds in accelerating global (green) growth to 35% annually from 2027, a dream of Silicon Valley optimists, the thermodynamic ceiling crashes down in roughly 26 years.

An implication from this paper is that the Industrial Revolution may have been premature. From the evolutionary model of carcinogenesis, it was suggested that longer-lived organisms (or civilizations) require more hard steps to prevent fatal growth - to develop better "immune policing" or (growth-suppressors) to manage the transition. Perhaps the Industrial Revolution was an energy revolution that occurred too quickly for human systems to manage. Perhaps it is the case that technologies of self-destruction grows faster than humanity's socio-political capacity to restrain them.

As a consequence, while mammalian species typically last about a million years (Gee, 2025), due to the Industrial Revolution, humanity's existence will likely be shortened to not much more than a third of this, $\approx 300,000+$ odd years.

The results of this paper have cosmic and metaphysical implications. Why is the universe silent? The Hard Steps model suggests that while getting to an industrial revolution is hard (taking 4.5 billion years), surviving it may be harder. It was calculated that there is a 95%

probability that humanity's technological civilization will last not more than 13,000 years, and likely end sooner, in 900 years - if one uses Bayesian probabilistic reasoning - or much less than 400 years, based on thermodynamic limits and the human climate niche.

The solution to Fermi's Paradox is then that the galaxy is a graveyard of post-industrial revolution that entered an economic growth spiral and collapsed before they could become space-faring or create durable techno-signatures. Or, alternatively, that there is a Great Silence because humanity is in an ancestor simulation of late-stage capitalism. A simulation that may eventually be switched off.

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