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Zeno's Paradox of Immortality

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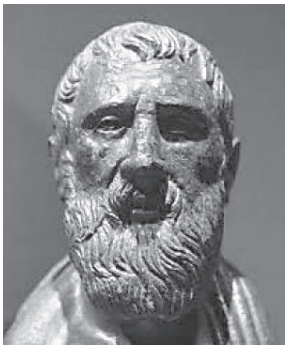
Abstract
Scientists who speculate on the future of human longevity have a broad range of views ranging from the promise of immortality, to radical life extension, to declines in life expectancy. Among those who contend that radical life extension is already here, or on the horizon, or immortality is forthcoming, elements of their reasoning appear surprisingly close, if not identical, to a famous mathematical paradox posed by the ancient Greek mathematician known as Zeno. Here we examine the underlying assumptions behind the views that much longer life expectancies are forthcoming or have already arrived, and place their line of reasoning within the context of a new Zeno paradox described here as *The Paradox of Immortality*.



'The slower will never be overtaken by the quicker, for that which is pursuing must first reach the point from which that which is fleeing started, so that the slower must always be some distance ahead.'

Zeno of Elea, a Greek philosopher born in ~450 BC, was famous for posing paradoxes that challenged mathematicians' view of the world. One paradox was known as *The Achilles* [1]:

The appealing logic behind *The Achilles* paradox, just as with all of Zeno's paradoxes, is that on the surface it sounds like a reasonable argument. After all, if one can explain through lucid reasoning and mathematics that halving the distance between two objects can occur indefinitely within a given time frame for an object in motion, then it is understandable why some would conclude that the fast will never outrun the slow, and an arrow shot at a tree will never meet its target. Zeno fools us into believing that space *and* time together can be divided into an infinite number of smaller pieces when applied to the action of moving objects – giving us the false impression

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that space is shrinking and time is slowing down. Of course, if Zeno was right, all movement would be impossible. The resolution to Zeno's paradox is that adding up an infinite number of small distances does in fact yield the finite distance that has to be travelled, which is the reason why the fast do outrun the slow and an arrow can reach its target. The problem is not so much with Zeno's mathematics, but the fact that space, time and moving objects do not operate this way.

Scientists who speculate on the future of human longevity have generated a broad range of views from the promise of immortality to anticipated future declines in life expectancy. Among those who contend that steady incremental increases in life expectancy will continue through the rest of this century, or that radical life extension is already here or on the horizon, four unique arguments have formed. Elements of their reasoning appear surprisingly close, if not identical, to Zeno's paradox.

One More Day of Life

Wilmoth [2] inquired whether there are limits to life, and chose to answer the question by using only the tools of a demographer or statistician. The central question asked was how death rates or life expectancy would behave if a limit to life were being approached. If the expected statistical behavior is not observed, he reasoned, then the hypothesized limit must be too far beyond the observed longevity horizon to be detected. The biology of life and death was disregarded in this quantitative analysis.

The evidence presented by Wilmoth [2] included: (1) data from Sweden for the period 1851–1990 that despite a high degree of variation in the age of the longest lived person did exhibit an increasing trend over this time period (based on data from one man and one woman from Sweden in each calendar year); (2) the hypothesis that a limited lifespan requires death rates to rise exponentially throughout the entire age structure – a pattern of mortality he suggested does not appear in humans (recent evidence indicates otherwise [3]); (3) the hypothesis that a decrease in the variability of death rates at older ages is not sufficient proof of a limit to life, and (4) the suggestion that the absence of a positive correlation between mortality level and the pace of mortality decline in some countries means a lower limit to the hazard function cannot be detected using demographic methods. The conclusion drawn from this analysis was that demographic/statistical evidence for a limit to life could not be detected.

Wilmoth [4] then carried his line of reasoning significantly further by concluding that 'over sufficiently long time periods, it is not at all unusual for death rates to decline by half or more', and therefore 'there is simply no convincing evidence (demographic, biological or otherwise) of a lower bound on death rates other than zero'.

Wilmoth's reasoning is predicated on the assumption that his demographic/statistical conditions do in fact reveal proximity to a limit to life. We suggest, however, there are no a priori reasons why death rates have to rise exponentially in order for a limit to be observed, or that mortality has to compress into a narrower age range, or that a positive correlation between level of mortality and pace of mortality decline is a defining characteristic of limits. The obstacle to this line of reasoning is the consistent message imposed by the force of mortality. Even when annual death rates of 50% are applied to a hardy group of survivors to extreme old age, everyone in every birth cohort eventually dies within a short time frame, even though statistical reasoning might lead some to believe otherwise. Very few people survive past age 115 and most deaths in any given cohort occur at highly regular ages that are tightly compressed within a few decades between ages 60 and 90.

The Zeno element in this line of reasoning, however, is the suggestion that survival time can forever be halved against a lower bound of zero, and that one more day of life can always be added. This purely mathematical line of reasoning does not apply to biological phenomenon, and it fails for the same reason the *Paradox of Achilles* fails – space and time, or in this case biology and time, do not operate this way. A simple example reveals the problem with the 'one more day' argument. Consider the world record for the one mile race. In the middle of the 19th century the record was 5.5 minutes, but it declined in linear fashion over the last 150 years to 3 minutes and 43 seconds today. Zeno might argue that there are no demonstrable reasons why one more second cannot always be shaved off this record – leading to the logical but untenable forecast that someone will eventually run a mile instantaneously. His argument could even be bolstered by a well-known biological fact – there is no genetic program in humans that precludes shaving time from the world record or, for that matter, running a mile instantly. Yet, common sense tells us that our body design will not allow this to happen. In similar fashion, while Wilmoth is correct in assuming that there is no genetic program that precludes the indefinite addition of one more day of life, the biomechanics of the human body does not allow

this to happen [5]. What Wilmoth fails to acknowledge is that in order to reduce death rates at advanced ages to zero or close to it, our biology would need to be modified. However, since he views human longevity and life expectancy limits purely through the lens of a statistician, he is unable to see the Zeno-like flaw with this line of reasoning.

Escape Velocity

De Grey [6] contends that dramatically longer human lives are attainable because *everything* that goes wrong with the body can be repaired with rapidly approaching near perfection, indefinitely. His logic is straightforward. De Grey claims that there are only seven categories of age-related molecular and cellular effects, which taken together, create the 'aging phenotype' (cell loss/cell atrophy, senescent/toxic cells, nuclear mutations/epimutations, mitochondrial mutations, extracellular cross-links, extracellular aggregates, and lysosomal aggregates). As such, creating rejuvenation therapies for all of them will allow the human lifespan to be extended indefinitely without any further advances in the biomedical sciences other than those yet to exist and nearly miraculous cures for aging.

De Grey then predicted with 90% confidence that a massive funding effort could produce the breakthroughs needed to achieve radical life extension somewhere between 2015 and 2040 – a statistical confidence derived from unknown sources since no data or rationale was provided for how such a confidence limit was computed or justified.

De Grey's Zeno-like reasoning appears not from his rationale for radical life extension, but from a demographic/actuarial concept he invented referred to as 'actuarial escape velocity' [7] which is described as a scenario where 'mortality rates fall so fast that people's *remaining* (not merely total) life expectancy increases with time. Is this unimaginably fast? Not at all: it is simply the ratio of the mortality rates at consecutive ages (in the same year) in the age range where most people die, which is only about 10% per year. I term this rate of reduction of age-specific mortality risk 'actuarial escape velocity' (AEV)…'. Since observed trends in death rates at older ages in long-lived populations have declined at a much slower rate than 10% in the recent past (on the order of 0.5–2.0%, with increasing death rates at some ages during some time periods [8]), de Grey is suggesting there is reason to believe that declines in death rates will soon accelerate dramatically at older ages. Indeed, he has predicted that at the oldest ages (past age 105) where annual conditional probabilities of death have consistently remained in the range of 50%, the probability of death will '…fall to 5% or lower, and mostly to below 1%...' [9, p. 393]. Evidence to support these forecasts was not provided.

This reasoning lead de Grey to suggest that period life expectancy, which is calculated based on the assumption that death rates from a single calendar year apply to a birth cohort for the remainder of their lives, dramatically underestimates cohort life expectancy (the observed duration of life of the cohort), and that this difference will increase over time. Interestingly, de Grey suggests his view is not scientific, but rather, it is based on the history of science and technology with anticipated fundamental breakthroughs driving large declines in future mortality [10]. However, even history does not support this position since the gap between cohort and period life expectancy at birth has fallen in the USA from 9.3 years in 1900 to 4.8 years today [11].

What is not apparent in de Grey's scenario is the 'cause' of accelerating declines in mortality; the therapies that simultaneously control his seven categories of biological aging are speculative both in content, and in particular, their potential impact on age-specific death rates. There is no current scientific basis to support the claim that life-extending technologies exist or can ever exist that are capable of generating survival time faster than it is consumed by living.

One critical question is whether permanent and continuous large declines in mortality are possible, and whether they yield mortality schedules that make biological sense. One reason for skepticism is the observation that the age-specific death rates used to estimate smooth trajectories of mortality are volatile, often vacillating from year to year. This temporal biodemographic heterogeneity is the rule, not an exception. Another source of departure from mathematical regularity is underlying cause of death. Cause of death changes in both kind and frequency across the age structure; as such, there is no justification or even historical precedent for assuming every cause-specific age trajectory should decline annually at a 10% (or greater) rate.

Although de Grey has identified only seven categories of aging that need to be fixed, there is no evidence that aging can be reduced to seven categories. The efficacy of his hypothetical interventions becomes less probable when it is recognized that aging is an unintended stochastic byproduct of the elegant but messy chemistry of life [12]. Firing a single arrow (intervention) at the bull's

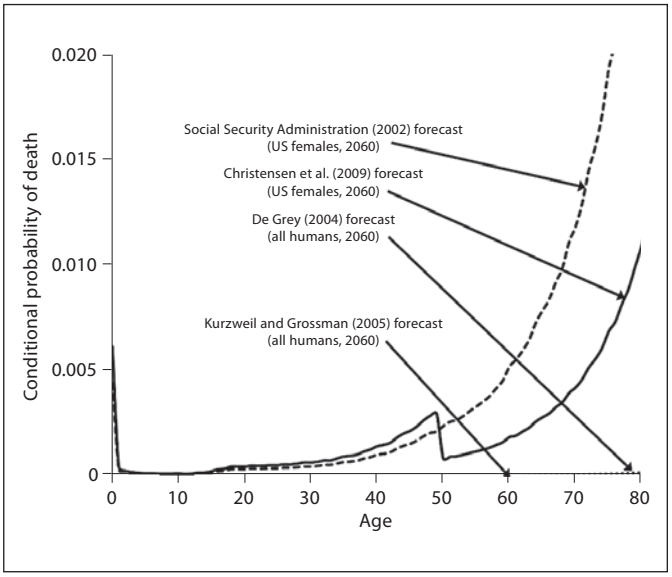

Fig. 1. Projected mortality schedule for US females (2060, ages 0–80) from the Social Security Administration (SSA) (2002), Christensen et al. (2009), de Grey (2004), and Kurzweil and Grossman (2005). We restricted the data to age 80 to illustrate the discontinuity present in the projected mortality schedule from Christensen et al. (2009). Exponential increases in mortality past age 80 are observed for the SSA (2002) and Christensen et al. (2009) forecasts, while the de Grey forecast would rise to about 0.01 mortality rate past age 105. The SSA forecast was derived from taking the projected $e_{(0)}$ for females and reducing death rates proportionally at all ages from a complete 2007 life table. The Christensen et al. (2009) forecast was calculated by reducing female death rates at ages 51 and older by enough to generate a 0.2 annual increase in $e_{(0)}$ beginning in 2007. The de Grey (2004) forecast was calculated by reducing death rates at all ages by 10% annually beginning in 2015, although roughly the same mortality schedule would result if the 10% hypothesized declines began in 2030. The Kurzweil and Grossman (2005) estimate is based on their assertion that everyone alive in the year 2025 will be immortal – thus yielding death rates of zero at all ages. All assumptions apply equally to males and females.

eye of a moving target (aging) is far easier than trying to hit any one of the pieces of a target shredded into thousands of pieces swirling in random fashion.

The biggest problem with de Grey's AEV concept is the extent to which the assumptions upon which it is based depart from historical precedent and biological constancy in age patterns of death. For example, among the longest-lived subgroup of humans who experienced the largest and most rapid declines in old-age mortality ever documented – Japanese females – the average improvement in the death rate among 85 year olds from 1950 through 2009 was 1.8%, and the rate of improvement has declined (not increased) since 2000 [8]. If declines in death rates at all ages declined by 10% annually as predicted under AEV, it would take about 36 years for death rates among the extreme elderly to reach the 1% threshold predicted, but the magnitude of the decline in the death rate would have to escalate rapidly at older ages and across time in order to yield equal annual increases in life expectancy. A visual image of the mortality schedule predicted by AEV for the year 2060 is provided in figure 1.

'Actuarial escape velocity' sounds appealing on the surface. However, the notion of manufacturing survival time faster than the rate of living (biological time) consumes it through the discovery and implementation of unspecified technologies whose unprecedented effects on age-specific death rates are based on speculation, is an exemplar of Zeno-like mathematics.

Bridges to Immortality

Kurzweil and Grossman [13] theorize that indefinite life is within reach for people alive today, if only they can 'live long enough to live forever'. According to the authors, this will be accomplished by crossing three hypothetical technological bridges to eternal life. 'Bridge One' technologies include nutritional supplements, changes in lifestyle, and extensive healthcare screening that in combination will allow people to live an additional 20 years beyond the life expectancies that prevail today. After 20 years, 'Bridge Two' biomedical technologies (e.g. stem cell therapy, genetic engineering, and 'rejuvenation technologies') are expected to emerge that will generate another 20 years of life. Around the middle of the 21st century, the expectation is that 'Bridge Three' technologies (e.g. nanotechnology) will make it possible to repair everything that goes wrong with the human body, leading to immortality.

One problem with this line of reasoning is the claim that behavior modification and nutritional supplements (which the authors sell at their website) can add 20 years to life expectancy today. The authors provide no empirical evidence to support this claim, and they do not reference the scientific literature demonstrating that even cures for cancer, heart disease and stroke will not add 20 years to life [14]. There is also no evidence provided to support the assertion that bridge two technologies will yield an additional 20 years of life; or exactly how a technology that does not yet exist – nanotechnology – will allow us to live forever.

What makes this line of reasoning resemble a Zeno-like argument is the phrase 'live long enough to live forever' – which is another way of saying that anyone who is alive in the year 2024 (20 years after their book was published) will be immortal. A visual image of the mortality schedule predicted by Kurzweil and Grossman for the year 2060 is provided in figure 1.

Radical Life Extension Has Already Arrived

It is one thing to suggest that immortality is within reach; it is another to assert that radical life extension is already available. The claim that babies born in the modern era *could* live to 100 years or more on average was originally made more than a quarter century ago [15]. This forecast has now been extended to a hypothesis that *most babies* born today in France and elsewhere [16] *will* live to 100 – a position recently expanded to other long-lived populations [17, 18] [(i.e., '…in countries with high life expectancies most children born since the year 2000 will celebrate their 100th birthday…' [17, p. 536]. This is not a 100-year life expectancy prediction, it predicts life expectancies greater than 100. How much greater is unclear since 'most babies' was not defined.

Based upon historical trends in life expectancy at birth observed over the last 200 years, Christensen et al. [18] claim that this trend (a 0.2-year annual increase) will continue from the year 2000 through the end of this century. Further, the mortality declines producing these gains must be restricted to the population aged 50 and older. Under this scenario, 50–75% (or more) of the babies born in 2000 and beyond will live to 100. The authors interpret mortality declines at older ages as a signal that the mortality consequences of aging are not only modifiable, but have already been successfully modified [17, p. 536].

Their assumption that the future repeats the past has already been violated; microbial deaths have been replaced by age-related diseases as the major causes of death. It is important to recognize that actuarial aging (a population phenomenon) has little or nothing to do with biological aging. Reliable biomarkers of aging do not exist and there is not even agreement on what causes aging or how aging relates to disease. Thus, the demographic claim that past declines in old-age mortality represent modifications to the aging process is incorrect [11]. Moreover, reducing the risk of death from fatal diseases that contribute to old-age mortality is not the same as delaying aging [19].

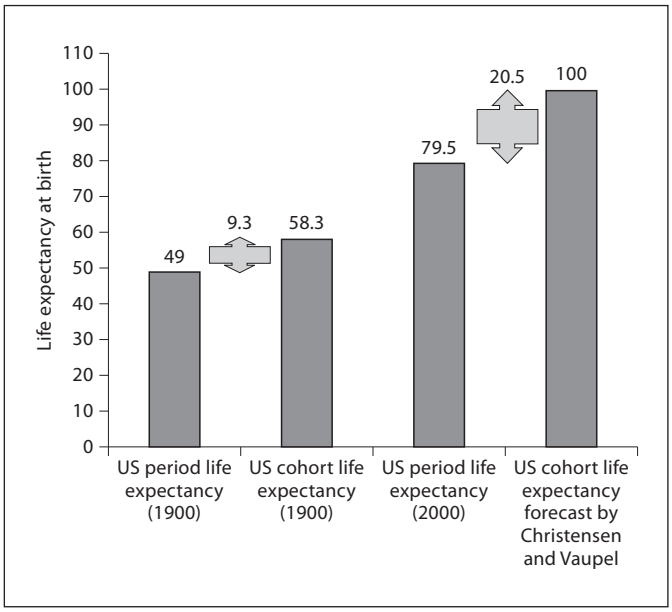

Fig. 2. Period and cohort life expectancy at birth (USA, 1900 and 2000). Sources: US period and cohort life expectancy at birth for the USA in both time periods is from the US Social Security Administration (SSA). Life tables for the US Social Security Area 1900–2100. Actuarial Study No. 116, 2002, SSA Publ. No. 11-11536. The estimate of cohort life expectancy at birth for the USA in 2060 is from Christensen et al. [18]. The difference between the 1900 period and cohort life expectancy estimates represents the observed empirical difference between these published numbers. The difference between the 2000 period and cohort life expectancy estimates represents a comparison of the projected cohort life expectancy in the year 2000 for the USA from Christensen et al. with a period life table published by the SSA. The observed difference in 1900 was 9.3 years; the projected difference according to Christensen et al., in 2000, is 20.5 years.

Compared to earlier predictions of immortality, the forecast of extreme life extension for 20th century birth cohorts may seem prudent. It is not. If 50% of the 2000 US female birth cohort lives to 100, then period life expectancy at birth in that year (79.5 years) is lower than cohort life expectancy at birth by 20.5 years. By way of context, the 9.3-year gap observed between period and cohort life expectancy at birth (49 and 58.3 respectively) for US females in 1900 occurred during a period (20th century) of unprecedented gains in life expectancy [20] (fig. 2). Thus, Vaupel and Christensen are forecasting life expectancy increases for 21st century birth cohorts that are 2.2 times faster than the unprecedented declines observed for 20th century birth cohorts. Importantly, these large increases in life expectancy are predicated on saving

the population aged 50 and older rather than the young as was done before.

This is not simply an extension of past trends into the future. Instead, it requires mortality at older ages to decline at a pace that is unprecedented. An unstated assumption is required for this logic to be correct, namely adding decades of life to people who have already aged for five decades or more will be easier than it was to add decades of life to children dying from infectious diseases.

The statement by Christensen et al. [18] that most babies born in the year 2000 in the USA will live to 100 appears even less plausible. One might conservatively interpret the phrase 'most children born since the year 2000 will celebrate their 100th birthday' [17, p. 536] to mean anywhere from 50 to 75% or more will survive to this age. Again for context, the US 2000 period life tables indicate that 1.8% of female babies born in that year are expected to live to 100 [8], a prediction that is 28 to 42+ times greater than current data suggest. Even in Japan where female life expectancy at birth is the highest in the world, only 4.5% of the 2000 female birth cohort is expected to live to 100 [8].

By holding mortality constant at 2006 levels for the population aged 0–50, Christensen et al. [18] are assuming that children born in 2000 will not experience the predicted benefits of declining middle- and old-age mortality until the year 2050 when the survivors will have already lived 50 years. Under this scenario, based on published period life tables for US females in 2006 [8], 4.6% of the original birth cohort would be expected to die by 2050, which means that over 75% of the survivors to age 50 would be expected to live another 50 years. By contrast, the probability of a 50-year-old female in the USA living for another 50 years in the year 2000 was only 1.9%. This unstated assumption is a notable departure from observed historical trends and actuarial probabilities.

The forecast by Christensen et al. [18] of 0.2-year annual improvements in life expectancy at birth (a 2-year gain per decade) invokes a linear increase in life expectancy. What the authors fail to disclose, however, is that this assumption requires accelerating declines in middle- and old-age mortality depending on when the life table is closed. For example, in 2007 with the life table closed at age 100, a 0.2-year gain in $e_{(0)}$ for US females (with all mortality improvements concentrated at ages 50 and older as the authors hypothesize) initially requires a 2.2% decline in death rates, but 50 years later the same 0.2 year gain in $e_{(0)}$ requires a 3.7% decline in death rates. The rising percentage reductions in death rates required to yield equal annual increases in life expectancy equivalent to that predicted by Christensen and colleagues was described more than two decades ago [21].

The Zeno-like element in this reasoning is the creation of an artificial set of mortality schedules for 20th century birth cohorts that violate the consistent mortality signature (age pattern of death) observed in human populations [22], and a hypothesized acceleration of declines in mortality occurring at ages progressively dominated by age-related diseases that currently have no cure. Notice in figure 1 what a mortality schedule for US females in 2060 would look like under the Christensen et al. [18] assumption of 0.2-year annual increases in life expectancy at birth. The same distorted mortality schedule would occur for males. Under this scenario, the risk of death for people who pass their 50th birthday drops dramatically to levels that are near zero and do not rise to levels experienced at age 50 until the cohort reaches age 71. This hypothesized mortality schedule has no precedent; it has never been observed in any human population.

The argument used to support linear increases in life expectancy at birth is roughly equivalent to suggesting that a runner will accelerate at an increasingly faster pace while running uphill on an increasing slope against a headwind of increasing resistance. Wilmoth [23, p. 1127] once said '…the burden of proof lies with those who predict sharp deviations from past trends.' Vaupel and Christensen and colleagues have not provided that proof.

Zeno's New Paradox: The Immortality

Zeno never posited a paradox called *The Immortality*, but if he had, it could easily be assembled from the lines of reasoning about the future of human longevity described above.

> 'If survival to age X is possible, and there are no biological or other reasons why survival to age X plus 1 day is not possible, then all we must do is reduce the risk of death to rates that match or exceed the passage of clock time, and we will become immortal.'

Whether the end result of this proposed new paradox is radical life extension or immortality is immaterial. The point we want to emphasize is that some researchers are suggesting that dramatic increases in life expectancy (and even immortality itself) are not myths or something to be achieved in the distant future. Instead, they suggest that these longevity outcomes are attainable or already available to most people alive today. If these assumptions are used to influence insurance premiums or

the funding of outlays for age entitlement programs, the public policy implications of this line of reasoning would be profound.

Conclusion

The *Paradox of Immortality* and the rationale behind it seem reasonable at first. Who could argue with the premise that just one more day of life is possible at any age, even if achieved through technologies that can only be dreamed of today? Continuous maintenance and repair of our bodies that approaches perfection is a laudable goal, but achieving it requires technological fixes and a human biology that simply do not exist [24]. Consider DNA repair, just one of the many components of a complex biology that would have to operate with near infallibly (through maintenance and/or repair) in order to achieve lifespans of thousands of years or more. This will not be easy to accomplish given that all current and future genetic material, if put end to end for each person at any given moment, would equal the distance of approximately 67 round trips to the sun [25]?

Since simple extrapolation models have predicted life expectancy in the present fairly well, it seems reasonable to assume that they will also predict life expectancy in the future. The main problem with this logic in the modern era of long-lived people is that it requires extending the lives of people who have already survived to later ages (manufacturing survival time) at a faster pace than the lives of infants were extended in the past. For example, a female infant born in the UK in 2009 had a life expectancy of approximately 82 years, which means a female baby whose life is saved by medical technology has the potential to survive 82 years. However, saving the life of an 82-year-old woman today manufactures only a small amount of survival time (frequently months, sometimes years, but rarely decades) [14]. Increasing the life expectancy of older people in the future at a much faster pace than was achieved for younger people in the past requires increasingly larger (nonlinear) reductions in death rates that are well beyond anything ever achieved in humans at any age. Indeed, almost all future declines in death will have to occur within older cohorts in order to achieve even linear increases in life expectancy, and this progress will have to occur during a time when even hypothetical cures for most major fatal diseases could not accomplish this feat [14], and when the health status of younger and older generations is already documented to be in jeopardy [26].

The mathematics behind the *Paradox of Immortality* may appear elegant, but its predictions of immortality or radical life extension require unprecedented and unrealistic assumptions about how the biology of an organism is altered by the passage of time. As such, linear forecasts of life expectancy, because of their requirement of accelerating reductions in old-age mortality against a backdrop of currently unyielding biological consequences of aging, are likely to generate dramatic overestimates of human longevity – especially if the forecasts extend for more than one or two decades.

The fundamental error in the *Paradox of Achilles* was the assumption that time and space could be halved indefinitely for a moving object, thus making it impossible to do something as simple as crossing the street. The essential error in the *Paradox of Immortality* is the belief that because there are no genetic programs for aging and death, that evolution does not measure time and therefore, we can forever add one more day of life; we can forever repair the damage that accumulates in our bodies – eventually with near perfection; we can forever build bridges to immortality, and we can assume that death rates for increasingly older generations will decline in the future at an accelerating pace.

Evolution does in fact measure time; it measures 'essential lifespan', the longevity window of survival time needed to achieve Darwinian fitness [27]. The biological events within this window – growth, development and maturation – and their temporal kinetics are under rigorous genetic control. Thus, essential lifespan *is* partially heritable. Survival beyond the essential lifespan; however, is not genetically orchestrated; there is no biological guarantee or even a need of one for extended lifespan or extreme longevity. The survival probabilities for extended lifespan are determined by an as yet unknown mixture of genes, behavior choices, environment and luck received and/or experienced within the essential lifespan [11]. The proponents of radical life extension are missing these proximate factors because they are looking in the wrong direction for answers to the question about whether limits on the lifespan of individuals and the life expectancy of populations exist – their gaze is exclusively focused only on the currently visible and a projected future lifespan horizon. Until they realize the biological answers to longevity limits and causes of aging are behind rather than in front of us, their visions for the future course of human longevity and life expectancy will continue to violate biological realities.

In the hypothetical race between Achilles and a tortoise, the slower can never be overtaken by the faster be-

cause the underlying assumptions about space, time and moving objects are false. In the *Paradox of Immortality*, radical life extension and immortal life sound plausible only because the underlying assumptions about biological time, and the forces that influence it, are either exaggerated or ignored. Immortality and eternal youth will remain wishful pursuits lacking scientific credibility and biological plausibility. There is, however, every reason to believe that progress in reducing avoidable mortality at middle and older ages will continue. Furthermore, modern science has made progress in understanding the biological determinants of longevity and aging with the intent of eventually using that knowledge to improve quality of life by extending the period of healthy life.

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