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Cover drawing of Great Basin Bristlecone Pine (*Pinus longaeva*) by Ed Monroe. According to dendrochronologists, these trees have been documented to live up to 5000 years.

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2 Human Longevity in Historical Perspective

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I. INTRODUCTION

Perhaps the greatest of all human achievements has been the enormous increase of human longevity that has occurred over the past few centuries. The average length of life in the early history of our species was probably in a range of 20 to 35 years (Table 2.1). By the beginning of the 20th century, this value had risen already to around 50 years in industrialized countries. One century later, the world's healthiest countries have a life expectancy at birth of around 80 years. Thus, around half of the historical increase in human life expectancy occurred during the 20th century. Of course, much of the increase in this average value has been due to the near-elimination of infant and childhood deaths. According to the available evidence, in the distant past, around a quarter of all babies died in their first year of life. Today, in the most advantaged countries, less than a half percent of infants meet a similar fate.

The increase of life expectancy at birth for one country, France, is depicted in Figure 2.1. This graph illustrates several key aspects of French demographic history over the past two centuries. First, we see the enormous increase of average human longevity over time, from a life expectancy in the high thirties during the early 19th century to values in the seventies or eighties at the end of the 20th century. Second, we witness the differential impact of the various wars on men and women. Two majors wars were fought mostly at the front and, thus, affected male life expectancy much more than female: the Napoleonic wars of the early 19th century and World War I during the 1910s. Two other conflicts involved a significant occupation of French territory by enemy forces and, thus, affected men and women in a similar fashion: the Franco-Prussian War of the early 1870s and World War II around the early 1940s. Finally, the graph illustrates the emergence of a large gap in life expectancy between men and women even during peacetime, from a difference of less than 2 years at the beginning of the interval to around 8 years at the end.

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TABLE 2.1
Life Expectancy and Infant Mortality Throughout Human History

	Life Expectancy at Birth (Years)	Infant Mortality Rate (per 1000 Live Births)
Prehistoric	20–35	200–300
Sweden, 1750s	37	210
India, 1880s	25	230
United States, 1900	48	133
France, 1950	66	52
Japan, 1996	80	4

Data from Acsádi, G. and Nemeskéri, J., *History of Human Life Span and Mortality*, Budapest: Akadémiai Kiadó, 1970; Davis, K., *The Population of India and Pakistan*, Princeton, NJ. Princeton University Press, 1951; Human Mortality Database, www.mortality.org.

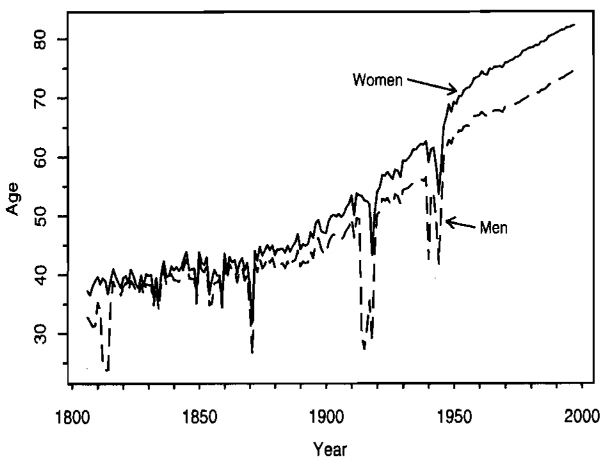

FIGURE 2.1 Life expectancy at birth by sex, France 1806–1997. (Data from Vallin, J. and Meslé, F., Tables de mortalité francaises 1806–1997, INED, Paris, 2000.)

The rise of human life expectancy is significant for several reasons. First, it reflects the increasing material comfort of human life over this period, as well as the technological and social advances associated with modern systems of public health and medicine. However, changes also come at a certain cost. Thanks to the "longevity revolution," industrialized societies are now faced with a large and growing elderly population (see Table 2.2), which poses a significant challenge in terms of medical care and social support. The rise in the proportion of elderly is balanced to some degree by a decline in the share of young people in the population, as illustrated in Figure 2.2 for Italy. To some degree, societies must merely reorient themselves toward the care of a large dependent population at the end of life rather than at the beginning of life. Such adjustments are not without costs, however, as the needs of children and the elderly are quite different. Therefore, careful social planning is required, based on a firm understanding of historical trends.

This chapter does not provide answers about how to make the needed social and economic adjustments. Rather, it attempts to explain the driving forces behind the increase of human longevity that accounts for this momentous shift in population distribution from younger to older ages.

II. HUMAN LONGEVITY IN THE PAST AND PRESENT

There are two important sets of questions about historical trends in mortality and health. First, how long do people live, why is longevity increasing, and how long will we live in the future? Second, given that we are living longer, are we mostly gaining healthy years of life, or are we "living longer but doing worse?" We know a lot more about the first question, partly because death is much easier to define and measure than health or functional status. In the United States, for example, there have been health interview surveys since the late 1950s and a consistent series of direct measurements of health status since the 1970s, in both cases, for a representative sample of the national population. These and similar data for other industrialized countries can be used to measure changes in health status, but it is often difficult to compare the results reliably across populations and over time.

On the other hand, we have detailed mortality data from many countries over much longer time periods. These data often include information on the attributed cause of death, although this concept, like health or functional status, is difficult to define and measure in a consistent fashion. Although there have been some attempts to measure early human longevity based on skeletal remains and other information,[1] the most useful information on historical mortality trends comes from time series of national data, collected since around 1750 in some parts of Europe. The accuracy of such data is variable, but specialists mostly know which data are reliable or potentially inaccurate. Data on cause of death must always be analyzed with great caution: although some trends are irrefutable (e.g., the historical decline of infectious disease), others appear contaminated by changes in diagnostic procedures and reporting practices (e.g., cancer trends, especially at older ages).

This section describes major trends in human longevity from the past and present. A later section of this chapter offers some guarded speculations about what the future may hold. We do not address the issue of "healthy life span," although the interested reader may refer to other sources on this topic[2,3] (see Chapter 3).

TABLE 2.2
Population of Major World Regions, 1950–2025, with Percent Under Age 15 and Over Age 65

Region	1950 Population Total (Millions)	1950 Percent Under Age 15	1950 Percent Over Age 65	1975 Population Total (Millions)	1975 Percent Under Age 15	1975 Percent Over Age 65
World	2521	34.3	5.2	4074	36.9	5.7
More developed countries	813	27.3	7.9	1048	24.2	10.7
Less developed countries	1709	37.8	3.9	3026	41.3	3.9
Africa	221	42.5	3.2	406	45.0	3.1
Asia	1402	36.6	4.1	2406	39.9	4.2
Europe	547	26.2	8.2	676	23.7	11.4
Latin America and Caribbean	167	40.0	3.7	322	41.3	4.3
North America	172	27.2	8.2	243	25.2	10.3
Oceania	13	29.8	7.4	21	31.0	7.5

Region	2000 Population Total (Millions)	2000 Percent Under Age 15	2000 Percent Over Age 65	2025 Population Total (Millions)	2025 Percent Under Age 15	2025 Percent Over Age 65
World	6055	29.7	6.9	7824	23.4	10.4
More developed countries	1188	18.2	14.4	1217	15.9	20.9
Less developed countries	4867	32.5	5.1	6609	24.9	8.5
Africa	784	42.5	3.2	1298	34.6	4.0
Asia	3683	29.9	5.9	4723	22.1	10.1
Europe	729	17.5	14.7	702	14.7	21.0
Latin America and Caribbean	519	31.6	5.4	697	23.7	9.5
North America	310	21.2	12.5	364	18.1	19.0
Oceania	30	25.2	9.9	40	21.3	14.6

Note: Figures for 2000 and 2025 are medium-variant projections.

Data from *World Population Prospects: The 1998 Revision. Volume 1: Comprehensive Tables*. New York, UN Population Division, United Nations, 2000.

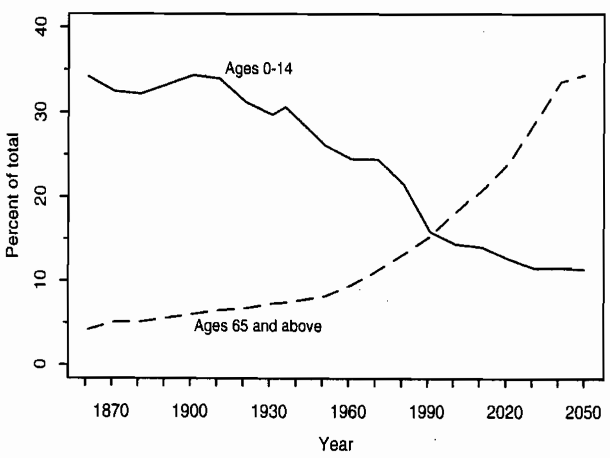

FIGURE 2.2 Proportion of population aged 0–14 versus 65+, Italy 1861–2050. Note: Figures for 2001–2050 are projections. (Data from Italian censuses, 1861–1991; ISTAT, 2001–2050.)

A. Prehistoric and Preindustrial Eras

We do not know much about how long humans lived before 1750. Around that time, the first national population data were collected for Sweden and Finland. For earlier eras, we have some life tables constructed for municipal populations, members of the nobility, and other groups that were probably not representative of the national population at large.[4,5] After 1750 and even today, we have extensive and highly reliable mortality information for only a subset of national populations.

For the Middle Ages and before, mortality levels have been estimated based on data gleaned from tombstone inscriptions, genealogical records, and skeletal remains.[1] The accuracy of such estimates has been a subject of dispute.[6–9] In studies based on skeletal remains, a key issue is the attribution of age based on bone fragments. Another problem for estimation based on skeletal or tombstone data is uncertainty about the age structure of the population, which affects mortality estimates based solely on the distribution of ages at death. The only practical solution is to assume that the population was "stationary," implying a long-term zero growth rate and unchanging levels of fertility and mortality, and even an unchanging age pattern of mortality. Clearly, these assumptions are always violated, but the resulting estimates are useful nonetheless.

For mortality data derived from subpopulations, there is also an issue of whether the data are representative of some larger population. Who gets buried in a society, and who gets a tombstone? Which societies have regular burial practices, as opposed, say, to burning their dead? What kinds of populations have complete genealogical records from a particular time period? Thus, for many reasons, all estimates of mortality or longevity from the preindustrial period (roughly, before 1750) should be viewed with caution. Of the many sources of bias in these estimates, there are positive and negative factors, which tend to balance each other to some extent.[10] They are inaccurate or unrepresentative by amounts that cannot be well quantified.

Although these historical estimates may be too high or too low, they provide us nonetheless with a useful description of the general contours of the history of human longevity. For example, most scholars agree that life expectancy at birth (or $\mathring{e}_0$, in the notation of demographers and actuaries) was probably in the twenties for early human populations. Some very disadvantaged societies might have had life expectancies in the teens, whereas others may have been in the thirties. Because historical levels of life expectancy were in the twenties, compared to around 75 to 80 years today in wealthy countries, the average length of life has roughly tripled.

Most of this increase was due to the reduction of infant and child mortality. It used to be the case, for example, that remaining life expectancy at age 1 year was greater than at birth, because the toll of infant mortality was so high. The difference between premodern periods and today is less stark if we consider life expectancy at higher ages. Instead of the tripling of life expectancy at birth, remaining life expectancy at higher ages has roughly doubled over the course of human history. At age 10 years, for example, life expectancy (i.e., expected years after age 10) may have moved from around 30 to 33 years to almost 70 years.[11] At age 50, it may have gone from around 14 years to more than 30 years.[10]

B. Epidemiologic Transition

The epidemiologic transition is the most important historical change affecting the level and pattern of human mortality. The transition refers to the decline of acute infectious disease and the rise of chronic degenerative disease.[12] This shift does not imply that degenerative diseases became more common for individuals of a given age. It merely means that infectious disease nearly disappeared, so something else had to take its place as the major cause of death. Increasingly, people survived through infancy and childhood without succumbing to infectious disease.[13] Once past these critical early years, survival to advanced ages is much more likely, and at older ages, various degenerative diseases present mortality risks even when infection is well controlled.

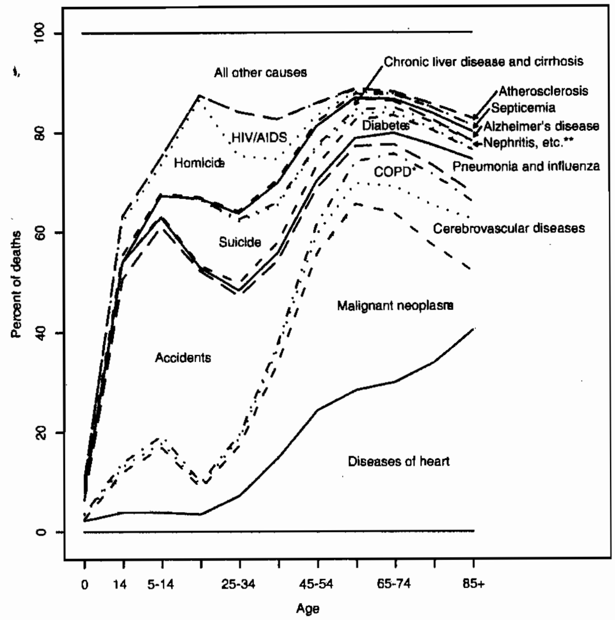

FIGURE 2.3 Distribution of deaths by cause, United States 1997. Notes:* Chronic obstructive pulmonary disorder; ** Nephritis, nephrotic syndrome, and nephrosis. (Data from U.S. Department of Health and Human Services, 1999.)

Thus, heart disease, cancer, and stroke became the most common causes of death in industrialized societies, as the age distribution of deaths shifted to older ages. As seen in Figure 2.3, which depicts the distribution of deaths by cause in various age groups for the United States in 1997, these three causes now account for more than 60% of all deaths at older ages. On the other hand, accidents, homicides, suicides, and HIV/AIDS are the major killers among young adults. Infants and children die mostly from accidents and "other causes" (a residual category that includes, for example, congenital anomalies and childhood diseases).

1. Trends in Life Expectancy

Life expectancy has been increasing not just in industrialized societies but also around the world. (During the 1990s, the two major exceptions to the worldwide increase in life expectancy were a stagnation and even reversal of earlier progress in parts of Africa, due to the AIDS epidemic, and in parts of the former Soviet bloc, especially Russia, due to social disruptions and instability.) The rise in life expectancy at birth probably began before the industrial era; thus, before national mortality statistics were first

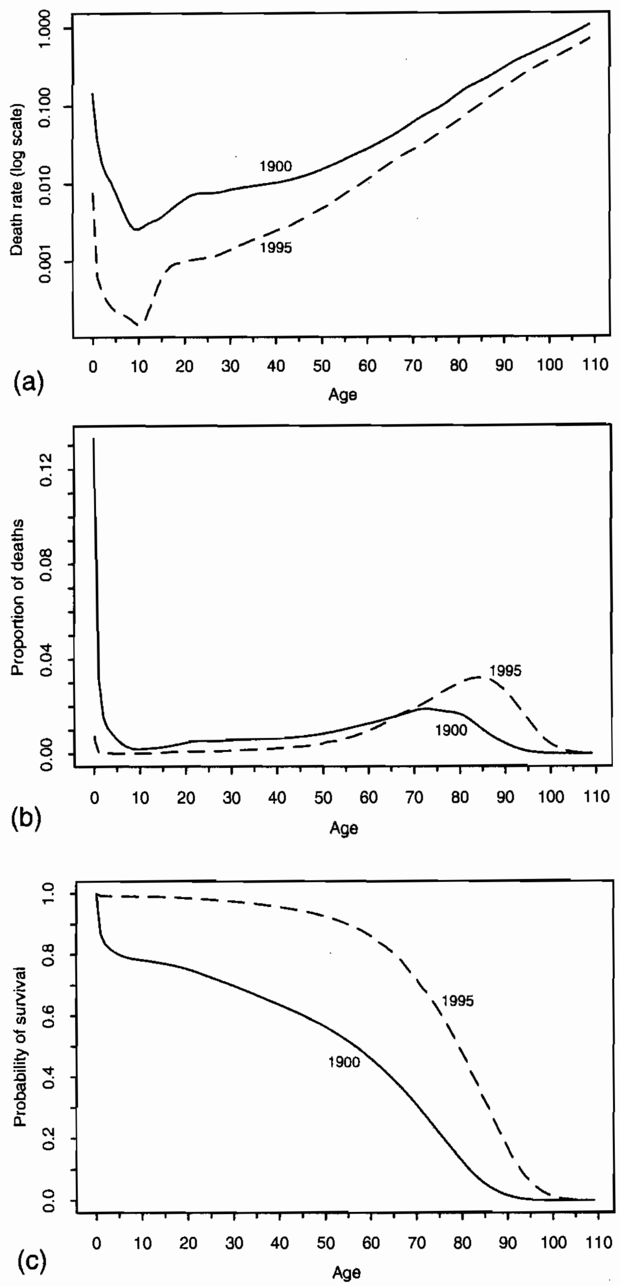

FIGURE 2.4 Age pattern of mortality from three perspectives, United States, 1900 and 1995: a) observed death rates by age, b) distribution of deaths by age, and c) proportion surviving by age. Note: Figures 4b and 4c present the distribution of deaths and the proportion surviving in a life table for the given year. (Data from U.S. Social Security Administration, available through the Human Mortality Database: www.mortality.org.)

assembled in Sweden around 1750. As noted earlier, $\mathring{e}_0$ (life expectancy) was probably in the twenties during the Middle Ages and earlier. By 1750, Sweden (and probably other parts of northwestern Europe) had attained an $\mathring{e}_0$ of 38, so the upward trend in longevity appears to have begun before the industrial era. Over the next century or more, there was a slow and irregular increase in life expectancy. After about 1870, however, the increase became stable and more rapid. During the first half of the 20th century, life expectancy in industrialized countries rose quite rapidly. Since 1950, the rise in life expectancy slowed somewhat, as seen in Figure 2.1 for France.

The cause of the earlier rapid rise in life expectancy and its subsequent deceleration is quite simple: the decline of juvenile mortality to historically very low levels. By around 1950, infant mortality in wealthy countries was in the range of 2 to 3% of births, compared to perhaps 20 to 30% historically. Since then, infant mortality has continued to decline and is now in the range of 0.5 to 1% of births in the healthiest parts of the world. As babies were saved from infectious disease, their chances of survival to old age improved considerably. Once juvenile mortality was reduced substantially, improvements in life expectancy due to the reduction of mortality in this age range had to slow, and further gains had to come mostly from mortality reductions at older ages.

The rise in life expectancy during the second half of the 20th century was slower than during the first half, simply because it depended on the reduction of death rates at older ages, rather than in infancy and childhood. Put simply, saving an infant or child from infectious disease, who then goes on to live to age 70, contributes more to average life span than saving a 70 year old from heart disease, who may live another 10 years. Thus, the deceleration in the historical rise of life expectancy is a product of the J-shaped age pattern of human mortality: high in infancy and childhood, low through adolescence and early adulthood, then rising almost exponentially after age 30. Gains that come from reducing juvenile mortality are quite large, whereas gains due to a reduction in old-age mortality are inevitably much smaller.

A common mistake is to assert that the deceleration in the rise of $\mathring{e}_0$ reflects a slowdown in progress against mortality. In fact, the reduction of death rates has changed its character in recent decades, but it has not slowed. At older ages, the decline of mortality has accelerated since around 1970 (as discussed below). So long as the decline of old age mortality continues, life expectancy will continue to increase, driven now by the extension of life at later ages rather than by saving juveniles from premature death.

2. Rectangularization or Mortality Compression

The age pattern of human mortality can be characterized in various ways. Figure 2.4 shows the American mortality levels in 1900 and 1995 from three perspectives. The first panel shows death rates by age. These death rates are used to construct a life table, which describes the experience of a hypothetical cohort subject throughout its life to the death rates of a given year. Thus, the middle and last panels show the distribution of deaths and the proportion of survivors at each age among members of such a hypothetical cohort.

Together, these three panels illustrate some major features of the mortality decline that has taken place over this time interval. First, death rates have fallen across the age range, but they have fallen most sharply (in relative terms, since the graph has a semilogarithmic scale) at younger ages. The distribution of ages at death has shifted to the right and become much more compressed. At the same time, the survival curve has shifted to the right and become more "rectangular" in shape. This last change is often referred to as the "rectangularization" of the human survival curve.

It was once asserted that this process of rectangularization reflected the existence of biological limits affecting human longevity.[14] This notion of limits to the human life span enjoys little empirical support, as discussed below. Nevertheless, the historical process of rectangularization was both real and extremely significant. It is perhaps best thought of as a "compression of mortality," as documented in the middle panel of Figure 2.4. As the average level of longevity has increased, so has our certainty about the timing of death.

One measure of this variability is the interquartile range of deaths in the life table or the age span of the middle 50% of deaths over the life course. In the 1750s in Sweden, the life table interquartile range was about 65 years, so that deaths were spread widely across the age range. The distribution of age at death became more compressed over the next two centuries, until the life table interquartile range was around 15 years in industrialized countries by the 1950s. Since 1960, there has been little further reduction in the variability of age at death in the developed world, even though the average age at death (as reflected in life expectancy at birth) has continued to increase.[15]

Like the historic rise of life expectancy, this compression of mortality was due largely to the reduction of juvenile mortality. Once most juveniles had been saved from premature death, a pattern emerged in which deaths are concentrated in the older age ranges. As mortality falls today among the elderly, the entire distribution of ages at death is rising slowly, but its level of variability seems to have stabilized.

C. Mortality Decline Among the Elderly

The most significant trend now affecting longevity in industrialized societies is the decline of death rates among the elderly. Until the late 1960s, death rates at older ages had declined slowly, if at all. Traditionally, rates of mortality decline were much higher at younger than at older ages. Since about 1970, however, there has been an "aging of mortality decline," meaning that some of the most rapid declines in death rates are now occurring at older ages.[16,17] Thus, the decade of the 1960s marks a turning point, from an earlier era of longevity increase due primarily to the decline of acute infectious disease among juveniles, to a more recent era involving the decline of chronic degenerative disease among the elderly.

1. Cardiovascular Disease

The most significant component of the mortality decline at older ages is the reduction of death rates due to cardiovascular disease (CVD), including heart disease and stroke. In the United States, heart disease has been the leading cause of death since 1921, and stroke has been the third most common cause since 1938. From 1950 to 1996, age-adjusted death rates for these two causes declined by more than half (by 56% for heart disease and by 70% for stroke). It is estimated that 73% of the decline in total death rates over this time period was due to this reduction in cardiovascular disease mortality.[18]

The exact cause of the decline in CVD mortality is open to debate, although it is surely due to a combination of factors. For the United States, all of the following have been cited as factors contributing to this decline: a decline in cigarette smoking among adults; a decrease in mean blood pressure levels; an increase in control of hypertension through treatment; a change in diet, especially a reduction in the consumption of saturated fat and cholesterol; and, an improvement in medical care, including better diagnosis and treatment of heart disease and stroke, the development of effective medications for treatment of hypertension and hypercholesterolemia, and an increase in coronary-care units and in emergency medical services for heart disease and stroke[18] (see Chapters 16, 17).

The rapid decline in CVD mortality began around 1968 in the United States and other industrialized nations. Given the precipitous nature of this decline, it has been argued that therapeutic interventions were the most important factor, because changes in diet and lifestyle should have led to a more gradual pattern of change.[19] It is worth noting that landmark investigations, like the Framingham Heart Study, began in the late 1940s and began to provide significant breakthroughs in our scientific understanding of cardiovascular disease during the 1960s.[20]

2. Cancer

In most developed countries, cancer mortality has begun to decline only within the last 10 to 15 years, although in Japan, death rates from cancer began falling as early as the 1960s.[21–23] Of course, cancer takes many different forms, and trends vary greatly by site of the primary tumor. Lung cancer has become more common due to increased smoking habits, while stomach cancer has been in decline. Among women, mortality due to cervical cancer has fallen dramatically thanks to successful medical intervention (screening and early treatment), while breast cancer has been on the rise due apparently to a number of interrelated factors (lower and later fertility, changes in diet, and possibly other factors as well).

It is sometimes overlooked that some common forms of cancer may be caused by infection. For example, stomach cancer is often brought on by infection with *Helicobacter pylori*. Infection with *H. pylori*, and hence stomach cancer, was especially common in Japan prior to the widespread availability of refrigeration.[24,25] Liver cancer is related to hepatitis infection (both the B and C strains of the virus), and thus reductions in liver cancer hinge on the control of infection, as well as curbing excess drinking. A third example is infection by the human papilloma virus, which can cause cervical cancer.[26]

These three forms of cancer have tended to decline in recent decades and should decline further as the relevant infectious agents are brought under control (e.g., hepatitis B and C). On the other hand, cancers that have become more common include those strongly influenced by individual behaviors (e.g., lung and pancreatic cancer are linked to smoking, and both have tended to increase over time) and some others with causes that are mysterious or poorly understood (e.g., breast cancer and colorectal cancer, both rising but for unknown or uncertain reasons).

As noted earlier, trends in mortality among the elderly are the main factor behind the continued increase in life expectancy in developed countries. Furthermore, the main components of mortality at these ages are cardiovascular disease and cancer. These two causes have been in decline during recent decades for reasons that are complex and not entirely understood. It is clear that there are multiple causes involved in bringing down death rates due to cardiovascular disease and cancer. Medical science has played a part, but so have changes in diet and personal habits, as well as community efforts and economic changes that have reduced the spread of infectious agents. It is important to keep this complex causality in mind when speculating about future trends in human mortality.

D. Summary of Historical Trends

A compact summary of major trends in human longevity in industrialized countries is presented in Table 2.3. Amidst the incredible detail available in historical mortality statistics, we cannot help but discern two major epochs: before 1960 and after 1970. The driving trend in the former period was a rapid decline of mortality due to infectious disease, which had an impact across the age range but certainly a much larger effect at younger ages. The sharp reduction in infant and child mortality led to a rapid increase in average life span and a marked reduction in the variability of age at death. It did not, however, have a major impact on maximum life span, which rose very slowly due to the more gradual improvement in death rates at older ages.

From the mid 1950s to the late 1960s, mortality trends in industrialized countries seemed to stabilize. Then, suddenly, just before 1970, death rates at older ages entered a period of unprecedented decline. Compared to the earlier era of rapid reductions in infant and child mortality, these changes yielded a slower increase in life expectancy at birth. On the other hand, the rise of maximum life span accelerated, driven by a more rapid decline in death rates at older ages. The variability of life span tended to stabilize during this period, as the entire distribution of ages at death (now concentrated at older ages) moved upward in parallel fashion. The difference between these two distinct eras is illustrated in Table 2.4 for the country of Sweden.

III. OUTLOOKS FOR THE FUTURE

It is impossible to make a firm scientific statement about what will happen in the future. In truth, scientists can only present the details of well-specified scenarios, which serve as forecasts or projections of the future. They can also help by clearly defining the terms of the debate, for example, by discussing what is meant by the notion of "limits

TABLE 2.3
Summary of Major Trends in Human Longevity in Industrialized Countries

	Before 1960	After 1970
Average life span (life expectancy at birth)	Increasing rapidly, because averted deaths are among younger people. Very rapid reduction in infant/child mortality linked mostly to effective control of infectious disease.	Increasing moderately, because averted deaths are among older people. Accelerated reduction in old-age mortality linked mostly to better management of cardiovascular disease.
Maximum life span (observed and verified maximum age at death)	Increasing slowly due mostly to gradual reductions in death rates at older ages. (Increases in births and improved survivorship at younger ages matter much less.)	Increasing moderately due almost entirely to accelerated reduction in death rates at older ages.
Variability of life span (standard deviation, interquartile range, etc.)	Decreasing rapidly due to reductions in mortality at younger ages.	Stable, because death rates at older ages are decreasing as rapidly as at younger ages.

TABLE 2.4
Change (Per Decade) in Key Mortality Indicators, Sweden

	1861–1960	1970–1999
Average life span (life expectancy at birth)	3.1	1.8
Maximum life span (maximum reported age at death)	0.4	1.5
Interquartile range (of deaths in life table)	-5.8	-0.3

Notes: Slopes are determined by least-squares regression.

For IQR (interquartile range), the range of the second time period is 1970–1995.

Author's calculations are based on data from Human Mortality Database, www.mortality.org.

to life span." Limits possibly affecting the increase of human longevity are the first topic of this section, followed by a discussion of extrapolative techniques of mortality projection or forecasting. Our discussion of the future of mortality concludes with a comparison of "optimistic" and "pessimistic" points of view on this topic.

A. Possible Limits to Life Span

If there are limits to the human life span, what do they look like? There are two ways to define such limits: maximum *average* life span and maximum *individual* life span.[16]

1. Maximum Average Life Span

Let us consider whether there might be an upper limit to the average life span that could be achieved by a large human population. Average life span, or life expectancy at birth, refers to how long people live on average in a population. In the United States, life expectancy is currently around 74 for men and 80 for women.[27] Accordingly, these numbers describe the average length of life that can be anticipated given the mortality conditions of today. For example, baby boys born this year will live an average of 74 years, assuming that age-specific death rates (as illustrated in Figure 2.4a) do not change in the future. Just as occurs today, some of these newborns will die in infancy from congenital ailments, some will be killed in car accidents as young adults, and some will succumb in old age to cancer or heart disease.

As noted earlier, death rates have been falling for several centuries. At every age, the risk or probability of dying is much lower than in the past. Thus, when we talk about life expectancy at birth, we are being conservative and asking what the average life span will be assuming that death rates do not fall any further in the future. However, it is likely that death rates will continue to decline at least somewhat in future years, so baby boys born today in the United States will probably live longer than 74 years on average.

The question about limits to the average life span can be posed as follows: Can death rates keep falling forever, or will they hit some fixed lower bound? Perhaps biological forces impose a certain inevitable risk of mortality at every age. Thus, there might be some age-specific minimum risk of dying that could never be eliminated.[16]

Admittedly, it seems implausible that age-specific death rates could ever equal zero in any large population. However, even if the death rate at some age cannot equal zero, can it keep declining toward zero? In other words, zero might be the limit to how far death rates can drop, even if they can never attain zero. Or is there a higher limit? Perhaps there is some number, like one in a million, such that it is simply inevitable that one in a million people — say, one in a million 50-year-olds — will succumb to death over the course of a year. If true, then the death rate at age 50 can never fall below one in a million. According to this view, we have a limited capability as a society, or as a species: we cannot push the risk of death any lower than some fixed level.

If a nonzero lower limit for death rates exists, how much is it at age 50 or at any age? The answer to this question is significant, for if we knew the lower limit of death rates at every age, we could compute the maximum achievable life expectancy at birth. In this way, we would know the upper limit of the *average* human life span. However, it is quite difficult to identify a nonzero lower bound on death rates that is applicable to all human populations. Yet, if there is no lower limit to death rates except zero, then there is no upper limit to life expectancy except infinity. Nevertheless, the absence of identifiable limits does not mean that large increases in average life span are imminent. It just means that life expectancy *can* continue to increase, as death rates are pushed down further.

Why do some people think that an upper limit to life expectancy exists? In fact, there is little empirical support for such a belief. An argument frequently put forward is that the rise in life expectancy at birth slowed in the second half of the 20th century. As shown earlier, however, this deceleration resulted merely from a shift in the main source of the historical mortality decline from younger to older ages. Although the rise in life expectancy has decelerated, the decline in death rates at older ages has accelerated in recent decades.[28]

Furthermore, if death rates are approaching their lower limit, one might expect a positive correlation between the current level of mortality in a given country and the speed of mortality decline (so that those populations with the lowest level of mortality would also experience the slowest rates of mortality decline). In fact, no such correlation exists for death rates at older ages. In some cases, the fastest reduction in death rates is occurring in those countries with the lowest levels of old-age mortality, just the opposite of what we would expect if death rates were pushing against a fixed lower bound.[28]

So long as death rates at older ages keep falling, life expectancy (at birth or at any age) will continue to increase. As discussed below, current forecasts suggest that life expectancy at birth may not rise much above current levels over the next half century. Nevertheless, there is simply no demographic evidence that life expectancy is approaching a fixed upper limit. Certainly, such a limit may exist, but it is nowhere in sight at the present time.[16]

2. Maximum Individual Life Span

Limits to average life span, or life expectancy at birth, are one issue. When people discuss limits to the human life span, however, they often have another idea in mind: the upper limit to an individual life span. Instead of asking how long we can live on average, we might ask how long one lucky individual can hope to live. This concept is actually much easier to understand than the notion of an upper limit to life expectancy.

Who is the oldest person who has ever lived? Even if we can never have a definitive answer to this question, we can at least imagine the existence of such a person. Maybe he or she (probably she) is still alive today. Or maybe she lived hundreds of years ago but vanished without leaving a trace — no birth certificate, no census record, and not even a newspaper article about her incredible feat of longevity.

Who is the oldest person alive today? That person might or might not be the oldest person ever. However, identifying the world's oldest person is difficult even today because of the widespread practice of what demographers politely call "age misstatement."[29] Putting it less politely, some people lie about their age. Others, if asked, give the wrong age because they do not remember, because they are not numerate, or because they simply never paid attention to such matters. Such age misstatement often occurs in the absence of written records to prove or disprove the reported age.

Should we believe people who claim to be extremely old but do not have proper documentation? Certainly, we should believe them because there is no point in calling anyone a liar or questioning their memory. In terms of a scientific discussion about longevity, however, experts agree that it is best to ignore undocumented cases of extreme longevity. Thus, when we make statements about who is the oldest person alive today or in the past, we limit ourselves to cases for which solid evidence exists.[30]

To be accepted as a valid instance of extreme longevity, thorough documentation is required — not just a birth certificate, but also a series of documents and a life history that is consistent with the written records. Ideally, if the person is still alive and mentally able, an oral history is obtained and checked against all available evidence, making sure, for example, that this person is not the son or daughter of the person in question.

Indeed, there are numerous examples of supposed extreme longevity that turned out to be cases of mistaken identity.[30] Perhaps the most notorious example was a French Canadian named Pierre Joubert, who was supposed to have died at the age of 113 years in 1814. This case was listed for many years by the *Guinness Book of World Records*.[31] When genealogical records were examined closely, however, two men named Pierre Joubert were identified — a father and his son. It was the son who died in 1814, 113 years after the birth of the father.[32] Such mistakes are not uncommon, and whether they are the result of deliberate misrepresentation or honest error is irrelevant. In either case, a complete investigation should be required before accepting such reports as factual.

The historical record is still held by a Frenchwoman, Jeanne Calment, who died at age 122 in August of 1997.[33] Madame Calment lived in Arles, a town with complete civil records (births, deaths, marriages, baptisms, etc.) going back several centuries. Fortunately, these records were not destroyed in any war, so it has been possible to carefully trace the life of Jeanne Calment. It was also possible to reconstruct her family genealogy and to document that a disproportionate number of her ancestors were long-lived as well. Of course, it is only one example, but the case of Jeanne Calment suggests that extreme longevity may have at least some hereditary component.[34]

The oldest man whose age was thoroughly verified was Christian Mortensen, who died in 1998 at the age of 115.[35,36] A Japanese man named Shigechiyo Izumi was reportedly 120 years old when he died in 1986. According to the *Guinness Book of World Records*, Izumi is still the oldest man on record.[31] However, this case has now been rejected by almost all experts who are familiar with it, including the Japanese man who originally brought it to the attention of *Guinness*.[37–39] The common belief is that Izumi was in fact "only" 105 years old at the time of his death.

It is reasonable to ask what we have learned in general from these few cases of exceptionally long-lived individuals. Admittedly, the cases of Calment and Mortensen tell us nothing about the trend in maximum longevity. Maybe these are just two cases that we have had the good fortune of documenting in recent years. Maybe there were other individuals who were just as old as Calment or Mortensen who lived years ago, and we missed them. These are valid points, so we must turn to other evidence if we want to know about trends in extreme longevity.

In order to study historical trends in extreme longevity, we need a well-defined population with reliable records over a long period of time. For that purpose, we turn to a small subset of countries that have kept reliable population statistics for many years. The longest series of such data comes from Sweden. These records are thought to be extremely reliable since 1861, even in terms of the age reporting of individuals at very old ages.[37] Vital records have a very old history in Sweden, where Lutheran priests were required to start collecting such information at the parish level in 1686. Such records were eventually brought together into a national system in 1749. In 1858, the present-day National Central Bureau of Statistics was formed, which led to further improvements in data quality. Furthermore, by the 1860s, the national system of population statistics was already more than 100 years old, so it was possible to check claims of extreme longevity against birth records from a century before. These historical developments account for the unique quality of the Swedish mortality data.

Figure 2.5 shows the trend in the maximum age at death for men and women in Sweden during 1861 to 1999. The trend is clearly upward over this time period, and it accelerates after about 1969. The rise in this trend is estimated to be 0.44 years (of age) per decade prior to 1969, and 1.1 years per decade after that date. More than two thirds of this increase can be attributed to reductions in death rates above age 70, with the rest due to mortality decline at younger ages and an increase in the size of birth cohorts.[40]

These Swedish data provide the best available evidence for the gradual extension of the maximum human life span that has occurred over this time period. Similar trends are evident for other countries as well, although patterns of age misstatement present greater problems of interpretation.[37]

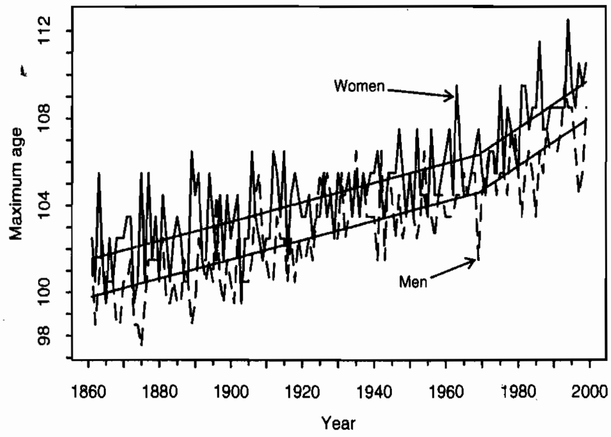

FIGURE 2.5 Maximum reported age at death, Sweden 1861–1999. (Source: Wilmoth, J.R., Deegan, L.J., Lundström, H., and Horiuchi, S., Increase of maximum life span in Sweden, 1861–1999, *Science*, 289, 2366, 2000. With permission.)

B. Extrapolation of Mortality Trends

Demographers claim some expertise in predicting future mortality levels, and their method of choice is usually a mere extrapolation of past trends. Biologists and others sometimes criticize this approach, because it seems to ignore underlying mechanisms. However, this critique is valid only insofar as such mechanisms are understood with sufficient precision to offer a legitimate alternative method of prediction. Although many components of human aging and mortality have been well described, our understanding of the complex interactions of social and biological factors that determine mortality levels is still imprecise. Furthermore, even if we understood these interactions and wanted to predict future mortality on the basis of a theoretical model, we would still need to anticipate trends in each of its components.

The extrapolative approach to prediction is particularly compelling in the case of human mortality. First, mortality decline is driven by a widespread, perhaps universal, desire for a longer, healthier life. Second, historical evidence demonstrates that mortality has been falling steadily, and life span has been increasing, for more than 100 years in economically advanced societies. Third, these gains in longevity are the result of a complex array of changes (improved standards of living, public health, personal hygiene, medical care), with different factors playing major or minor roles in different time periods. Fourth, much of this decline can be attributed to the directed actions of individuals and institutions, whose conscious efforts to improve health and reduce mortality will continue in the future.

Even accepting this argument, there is still a question of what to extrapolate. Demographers tend to view death rates as the fundamental unit of analysis in the study of mortality patterns, because these rates are estimates of the underlying "force of mortality," or the risk of death at any moment in a person's lifetime. These risks change over age and time, and vary across social groupings (by sex, race, education, income, etc.). Life expectancy and the expected maximum age at death (for a cohort of a given size) can be expressed as a mathematical function of death rates by age. Thus, the usual strategy is to extrapolate age-specific death rates into the future and then to use the results of such an extrapolation to compute forecasts of life expectancy or other parameters of interest.

Predictions of future life expectancy by such methods yield values that are not too different from what is observed today. For example, recent forecasts by the U.S. Social Security Administration put life expectancy in 2050 at 77.5 years for men and 82.9 years for women, compared to 72.6 and 79.0 years in 1995.[41] These forecasts are not true extrapolations, however, because they assume a slowdown in age-specific rates of mortality decline in the future. Another study, based on a purely extrapolative technique, yielded more optimistic results — a life expectancy at birth in 2050 of around 84 years for both sexes

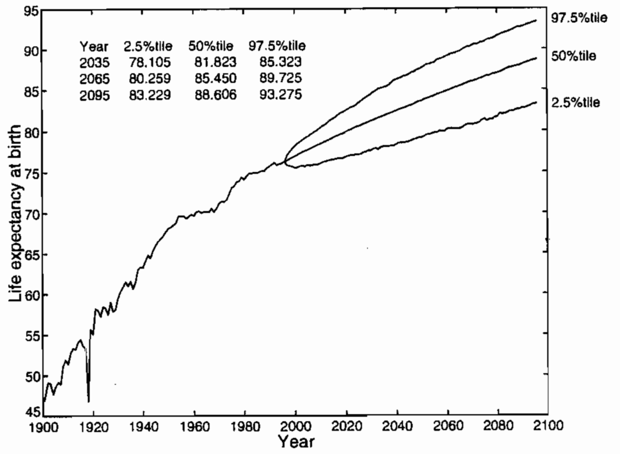

FIGURE 2.6 Life expectancy at birth, United States, 1900–1996 (actual) and 1997–2096 (forecast). (Source: Lee, R. and Tuljapurkar, S., Population Forecasting for Fiscal Planning: Issues and Innovations, *Demographic Change and Fiscal Policy,* 1st ed., Cambridge University Press, Cambridge, Chapter 2, 2001. With permission.)

combined.[42] Plausible forecasts for Japan are only slightly higher life expectancy at birth in 2050 of 81.3 years for men and 88.7 years for women, compared to 76.4 and 82.9 years in 1995.[43]

The life expectancy forecasts of Lee and Tuljapurkar[42] are reproduced here as Figure 2.6. These projections are based on a clever extrapolative technique pioneered by Lee and Carter,[44] which has been influential in the world of mortality forecasting over the last decade. The method yields a range of estimates for each calendar year during the forecast period (in this case, from 1997 to 2096). The inherent uncertainty of future trends is represented in the graph by plotting not only the median forecast, which may be considered the "best estimate," but also by showing two extreme forecasts. The median forecast lies at the fiftieth percentile of the full distribution: half of the estimates lie below or above this value. Figure 2.6 also presents the 2.5 and 97.5 percentiles, thus showing relatively extreme trajectories of future life expectancy.

It is important to remember that these projections are mere extrapolations of the historical experience of one country during a particular time period (the United States from 1900 to 1996). The implicit assumption is that future trends will resemble past ones. This assumption is plausible given the fairly steady pace of mortality decline over the past century. Of course, extrapolation is not without its flaws. It could not, for example, have anticipated the rise of mortality in the former Soviet Union after 1990, the emergence of AIDS in certain populations during the 1980s, or the divergence of mortality trends between Eastern and Western Europe after 1960. However, such observations are less an indictment of extrapolation as a method of mortality forecasting than a demonstration that the greatest uncertainties affecting future mortality trends derive from social and political, rather than technological, factors.

An important issue for consideration in forecasting mortality is the time frame, both the time frame of the data that form the input to an extrapolation and the time horizon of the projection. Although short-term fluctuations have been common, long-term mortality trends in industrialized countries have been remarkably stable. When mortality decline slowed temporarily during the 1950s and 1960s (in the United States and other developed countries), predictions that the rise in human life expectancy had come to an end were commonplace. Similarly, the unusually rapid decline of mortality rates after 1968 fostered expectations of unprecedented gains in longevity that would continue for decades. With the benefit of hindsight, these were both overreactions to rather short-lived episodes in the history of mortality change.

Another common error results from an undue emphasis on trends in life expectancy. Although it continues to increase, the pace of change in life expectancy at birth has slowed in recent decades relative to the first half of the 20th century (see Figure 2.1). As noted earlier, this slowdown was inevitable once juvenile mortality was reduced to historically low levels. However, it does not follow from this observation that gains against mortality in the future will be slower than in the past. Although the increase in life expectancy has slowed, the decline in death rates at older ages (where most deaths now occur) has quickened.[28] An extrapolation of current trends in death rates suggests that life expectancy will continue to increase, though not as quickly as during the first half of the 20th century. This slow but stable increase in average life span will be driven by the accelerating pace of mortality decline at older ages.

C. Optimism Versus Pessimism

In recent years, the extrapolative approach to mortality prediction has been challenged by assertions that future changes in average human life span may come more or less quickly than in the past. The more optimistic view that life span will increase rapidly in the near future is partly a result of the acceleration in rates of mortality decline among the elderly in developed countries during the past few decades. From an historical perspective, however, this change is relatively recent and should be extrapolated into the future with caution. If the new pattern persists for several more decades, it will then constitute strong evidence that old trends have been replaced by new ones.

Another source of optimism about future mortality rates lies in the potential application of existing technologies (e.g., nutritional supplements, reductions in smoking) or the unusual longevity of certain groups, such as

Mormons and Seventh Day Adventists.[45,46] Such discussions may be a good way to improve health behaviors, but they are not so good at informing predictions, largely because this same sort of advocacy influenced past trends as well. For purposes of prediction, we need to ask whether future positive reforms in lifestyle are likely to be implemented faster or more effectively than were similar reforms in the past.

From time to time, technological breakthroughs provide another source of optimism about future mortality rates. In 1998, the manipulation of a gene that halts the shortening of telomeres during the replication of human cells *in vitro* was a source of great optimism in the popular media, provoking rather extraordinary claims about the possibility of surviving to unprecedented ages in the near future. Talk of cures for cancer and vaccines against AIDS promotes similar hopes. Such discussions should not be dismissed as mere wishful thinking but should also be seen in historical perspective.

As wondrous as they may be, recent scientific advances should be compared, for example, to Koch's isolation of the tubercle bacillus in 1882, which provided confirmation of the germ theory of disease and led to a great flourishing of public health initiatives around the turn of the century, or to Fleming's discovery of the antibacterial properties of penicillin in 1928, an event that led to the antibiotic drug therapies introduced in the 1940s. Extrapolations of past mortality trends assume, implicitly, a continuation of social and technological advance on a par with these earlier achievements.

More pessimistic scenarios of the future course of human longevity are based on notions of biological determinism or arguments about practicality, yielding the now-familiar claim that life expectancy at birth cannot exceed 85 years.[14,47] Sometimes, evolutionary arguments are invoked in support of the notion that further extension of the human life span is impossible, even though existing theories say little about whether and to what degree the level of human mortality is amenable to manipulation.[48]

Current patterns of survival indicate that death rates in later life can be altered considerably by environmental influences, and there is little conclusive evidence that further reductions are impossible. Furthermore, as noted before, trends in death rates and in maximal ages at death show no sign of approaching a finite limit. Nevertheless, although claims about fixed limits to human longevity have little scientific basis, a life expectancy at birth of 85 years, the oft-postulated theoretical limit, is within the range of values predicted by extrapolative methods through the end of the 21st century (see Figure 2.6). In contrast, more optimistic claims, a life expectancy at birth of 150 or 200 years, or even more, are much farther afield and would require a much larger deviation from past trends.

D. Learning from History

The historical rise of human longevity is the result of a complex set of changes beginning several centuries ago. Prior to the 1930s, most of this decline was due to factors other than medical therapy,[49] and it is generally attributed to improvements in living conditions and public health. With the advent of antibacterial drugs in the 1930s and 1940s, medical treatment began to play an important role in these changes, and this role has expanded in recent decades thanks to interventions in cardiovascular disease and cancer, which have contributed to the rapid decline of old-age mortality.

It seems reasonable to expect that future mortality trends in wealthy nations will resemble past changes. Although the focus of our efforts will evolve, the net effect on death rates will probably be similar. For this reason, extrapolation is the preferred means of predicting the future of human mortality. This strategy rides the steady course of past mortality trends, whereas popular and scientific discussions of mortality often buck these historical trends, in either an optimistic or pessimistic direction. History teaches us to be cautious. Pessimism about the continuation of mortality decline is not new, and earlier arguments about an imminent end to gains in human longevity have often been overturned, sometimes quite soon after they were put forth. On the other hand, dubious claims about the road to immortality are probably as old as human culture, even though they have not influenced official mortality forecasts as much as their more pessimistic counterparts.

Although imperfect, the appeal of extrapolation lies in the long-term stability of the historical mortality decline, which can be attributed to the complex character of the underlying process. This combination of stability and complexity should discourage us from believing that singular interventions or barriers will substantially alter the course of mortality decline in the future. In this situation, the burden of proof lies with those who predict sharp deviations from past trends. Such predictions should be based on theoretical results that are firmly established and widely accepted by the scientific community. Certainly, history can be overruled by a genuine consensus within the scientific community, but not by unproven theories, intuition, or speculation.

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