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The Value of Life in General Equilibrium

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PRELIMINARY AND INCOMPLETE

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Abstract

Perhaps the most important change of the last century was the great expansion of life itself—in the US alone, life-expectancy increased from 48 to 78 years. Recent economic estimates confirm this claim, finding that the economic value of the gain in longevity was on par with the value of growth in material well-being, as measured by income per capita. However, ever since Malthus, economists have recognized that demographic changes are linked to economic behavior and vice versa. Put simply, living with others who live 78 years is different than living with others who live only 48 years, so that valuing the extra 30 years of life is not simply a matter of valuing the extra years one lives. Incorporating the general equilibrium effects of changes in life-expectancy, we attempt to estimate its effect on the value of life relative to previous partial equilibrium valuations. Measured in dollar terms, much of the effect of longer life does not accrue to the persons whose lives are extended because longer life affects the size of the population. With guidance from previous literatures on the demand for labor, increasing returns to population, and life cycle savings, we embed a model of life extension in a larger general equilibrium model of population. Focusing on the gains in life-expectancy in the United States from 1900 to 2000, we find that a significant part of the value of longer life is due to these general equilibrium effects. Our estimates suggest that the partial equilibrium value of survival gains in the 20^{th} century United States may understate the true general equilibrium gains by as much as a third.

I. INTRODUCTION

The 20th century witnessed tremendous advances in health, from the development of the germ theory of disease to antibiotics for infectious disease and to genetic testing for inherited conditions. Indeed, it seems hard to argue that any one change during this last century was more important than the expansion of life itself. Given the importance of this growth in life, relatively little effort has been made by economists to measure and value it, especially compared to research efforts devoted to analyzing growth in per-capita income.

There is a growing consensus among economists that the total economic value of gains in longevity and health swamped the single accomplishments of some of the largest advances in the past hundred years, from such breakthroughs as railroads, aviation, and the internet. Indeed, a substantial amount of recent work indicates that the gain in human longevity is the most important economic advancement over the last century as indicated by a growing literature that attempts to value these gains in health relative to gains in per-capita income. For the US alone, Cutler and Richardson (1997), Nordhaus (2003), and Murphy and Topel (2006) all estimate that longevity gains have been on par in value to the gains in material well being from income growth as measured by traditional income account measures. For the world as whole, Becker, Philipson, and Soares (2005) argue that changes in inequality are greatly affected by incorporating longevity into national income accounting. This strand of work uses traditional micro-economic equilibrium methods to monetize the value of gains in longevity and then compare those monetized gains to gains in income (see e.g. Rosen (1988)), in the sense that what is valued is a change in longevity itself, holding other factors constant.

However, longevity affects the levels and growth of economic income and therefore ignoring these effects in the value of increased longevity may be misleading. There are several ways in which longevity may affect income. The most direct is through population size. Ever since the pioneering work of Malthus (1798), economists have appreciated the importance of the effects of population size on economic well-being and national income levels. Indeed, as fertility has been falling and longevity growing, the growth in longevity is an important source of the increased size of populations in many countries, and thus an important source of the effects of population on growth and vice versa. Another way in which increased longevity may affect income is through increased savings incentives and thus capital accumulation, whether it be physical or human capital oriented. Lastly, an important non-Malthusian mechanism by which longevity may affect income is through the increased incentives for innovation induced by longevity alone, as it implies larger markets (see e.g. Acemoglu and Linn (2004) and Philipson and Geoffard (2002)). Indeed, there is long standing and large literature stressing both the negative and positive impact of population growth on both economic income levels and growth (see e.g. Bloom, Canning, and Sevilla, 2003), that implicitly provides evidence on the effects of longevity on economic performance.

In this paper, we attempt to reconcile these two separate strands of research efforts by incorporating the *general equilibrium* effects of increased longevity into estimating the value of the gains in longevity. Our approach is in contrast with previous work assessing the value of the growth in longevity which is a *partial equilibrium* approach, assuming non-existent the important demographic effects that impact economic growth. When longevity is increased, it raises population size, which in turn impacts income levels, though with different effects dependent on whether there are decreasing or increasing returns to scale in production. Our main argument is that the general equilibrium price-effects induced by increased longevity greatly alter estimates of the value of this increased longevity from those obtained using a partial equilibrium approach that ignores them.

More precisely, we first value the partial equilibrium gains in US survival in the last century (1900 to 2000), a period in which life-expectancy rose nearly 30 years, from 48.2 to 77.6 years. Holding fertility behavior constant and netting out the impact of immigration, we estimate that this gain in longevity alone would have increased the US population by almost 300 percent in 2000 compared to 1900 levels. Using existing estimates from the literature on the effects of population on income, we calibrate that PE estimates of the value of survival gains in the 20th century United States may understate the true gains by as much as a third, so that the true gains are nearly three times as large as current PE estimates. We find similar effects when considering the effects of life-expectancy on investment choices that also raise income. Viewed in another way, current PE estimates (Murphy and Topel, 2006) suggest that the value of 20th century health improvements range from 10 to 50 percent of per capita income, while our calibrations suggest that the true value of health gains could be worth an additional 1-2 times per capita income.

The paper may be outlined as follows. Section II illustrates the bias in partial equilibrium estimates of the value of life and demonstrates how existing empirical relationships between longevity and income can be incorporated to quantify its size and direction. Section III uses this methodology to calibrate the partial equilibrium value of improved longevity in the United States during the last century. Section IV compares these gains to new general equilibrium estimates, which incorporate the empirically observed effects of longevity on the level of income. Lastly, Section V concludes and discusses future research.

II. PARTIAL vs GENERAL EQUILIBRIUM VALUATION OF LIFE

A. Valuing Improvements in Health and the PE-GE Bias

Following Becker et al. (2005), we value the gains in longevity in a given period by considering a hypothetical individual born in calendar year t who faces cross-sectional survival (S_t) and lifetime net income given by:

$$Y(A_t(S_t), I_t, E_t) = A_t(S_t)\, y(I_t, E_t) \qquad (1)$$

where $A(S_t) = \sum_{a=0}^{\infty} \beta^a S_t(a)$ is the present value of an annuity paying one dollar per year given survival S_t and discount rate β, and $y(I_t,E_t)$ is annual net income which, for simplicity, is assumed to be constant over time and equal to its value in calendar year t.

Lifetime net income is defined as gross income net of all investment expenditures and is determined by three factors. The first is the period of time over which annual net income y is earned, captured by $A(S_t)$. The second is a set of "internal" behaviors denoted by I_t – namely behaviors chosen by the individual to maximize his utility. These behaviors may include decisions over one's own human capital investment, life cycle savings, and family formation, all of which are affected by life expectancy and likely chosen to maximize utility. Each of these investments may raise lifetime gross income, but presumably only at a cost, whether in foregone earnings, tuition, delayed marriage, etc. In theory, net income is intended to adjust for these costs. For example, consider an investment in education due to improved longevity that results in an increase in lifetime gross income of $500,000. If the cost of tuition and foregone earnings were $200,000, focusing on gross income would lead us to incorrectly calculate the effect of improved longevity on income to be $500,000, rather than the $300,000 that would obtain when investment costs are considered.

The third determinant of lifetime net income is a set of "external" behaviors denoted by E_t – namely outcomes (typically determined by others) that do not necessarily maximize utility but nonetheless are affected by survival. The total size of the population at various dates is the primary example we consider – it depends on the survival rates of all persons in the economy and does not necessarily maximize anyone's utility.[1] An individual's income might be affected by the number of persons alive because (a) the extent of the market affects the number of products available (e.g., aggregate increasing returns to research and development), and (b) the extent of the market affects the variety

[1] For example, consider a birth cohort of size n_t born in year t that lives to age a with probability $S_t(a)$. The population size in any year t is then determined by $N_t = \sum_{k=-\infty}^{t} n_k S_k(t-k)$.

of products available.[2] We normalize the measurement of I_t and E_t so that they increase, rather than decrease, annual net income y.

The lifetime indirect utility for an individual of cohort t is:

$$V[Y(A(S_t), I_t, E_t), A(S_t)] \quad = \quad \max A(S_t)U(c_t) \quad s.t. \quad A(S_t)c_t = Y(A(S_t), I_t, E_t) \qquad (2)$$

By having the same discount factor in both the preferences and the budget set, we are implicitly abstracting from life-cycle consumption profile decisions—cohort t's decision, then, is only about the average amount to consume in every year c_t. Moreover, since our hypothetical individual is assumed to derive utility only from consumption, the benefits and costs of human capital investment and other behaviors are fully captured in the maximized lifetime net income Y.

An individual's *partial equilibrium* (PE) willingness to pay, P_{PE}, for an increase in survival from S to S' holds constant the effects of survival on internal and external behaviors, implicitly assuming away (or approximating as zero) the effects on income of changes in own-investment and population size:

$$V[Y(A(S'), I, E) - P_{PE}, A(S')] = V[Y(A(S), I, E), A(S)] \qquad (3)$$

That is, P_{PE} is the amount an individual is willing to pay to be just indifferent between the two survival prospects, S and S', holding constant the internal and external behaviors.

The PE willingness to pay does not account for the changes in the population, or changes in the individual's own behaviors, that result from the increased life-expectancy. For small changes in survival, the envelope theorem tells us that, even though the PE willingness to pay holds many things constant, it still captures the induced changes in any *internal* behavior I_t that already maximizes V for a given survival, because those induced changes have no utility value at the margin. However, while schooling, life cycle savings, and other personal decisions may well be optimally chosen by each individual, for large changes in survival, the utility value of new choices may not be zero. Moreover, even for small changes in survival, the envelope theorem does not apply to the effects of survival on population size and (other external behaviors) since there is no obvious reason why total population would maximize the representative individual's utility. For example, important activities like innovation have socially increasing returns. Finally, the envelope theorem does not apply when evaluating the effects of survival on outcomes other than utility, e.g. income inequality. In this case, even marginal changes

[2] The potentially positive income effects of population growth may come at cost as well. These costs would in theory also be captured by the net income above.

in survival may have an impact, although behavior-induced effects on utility would be absent.

Given the various channels through which changes in survival may affect income, the *general equilibrium* (GE) willingness to pay is determined by:

$$V[Y(A(S'), I', E') - P_{GE}, A(S')] = V[Y(A(S), I, E), A(S)] \qquad (4)$$

where *E'* reflects the effects of changes in survival on population and other external behaviors, and *I'* reflects the effects of changes in survival on internal behaviors. While the PE willingness to pay is bounded by the net lifetime income available under survival S, the GE willingness to pay is bounded by the net lifetime income available under the new survival, S'. Put differently, the GE willingness to pay for improved survival reflects the value of not only longer life, but of the potentially disproportionate change in net lifetime income resulting from individual *and* aggregate increases in longevity. Specifically, the above expression illustrates that the GE value of improved longevity, which incorporates the income effect of improved health, differs from its PE counterpart by:

$$P_{GE} - P_{PE} = Y(A(S'), I', E') - Y(A(S'), I, E) = A(S')[y(I', E') - y(I, E)] \qquad (5)$$

The PE-GE bias, then, is the discounted change in net lifetime income holding survival fixed at its new value. When changes in survival have no effect on the evolution of net annual incomes, either directly or through changes in population size, the bias is zero. Moreover, expression (4) demonstrates that an upper bound of the PE-GE bias is the present value of the differences in *gross* annual incomes. Since the potential increases in income that result from survival improvements presumably come at a larger cost of investment, using net incomes which adjust for these costs would lower the computed bias.

Different techniques are appropriate for calculating the PE-GE bias due to internal versus external behaviors. The envelope and intermediate value theorems suggest that the bias due to the *internal* behaviors can be bounded by re-evaluating the PE bias at final values, rather than initial values.[3]

[3] Consider the simple case where individuals care only about expected lifetime earnings given by $V = \max_h py(h) - h$, where h is the investment in human capital and p is the probability that one survives to earn income y(h). Given an initial survival p_o, $h^*(p_o)$ is chosen optimally to maximize V. By the envelope theorem, the PE value of a marginal increase in p is simply $y(h^*(p_0))$. Thus, for a small change in survival, there is no bias in the PE value of life, since h* does not change. Now consider an infra-marginal change in survival from p_0 to p_1. The PE value of life is $[p_1 y(h^*(p_o)) - h^*(p_o)] - [p_o y(h^*(p_o)) - h^*(p_o)] = (p_1 - p_o) y(h^*(p_o))$. The GE value of life, which accounts for the effect of the change in p on human capital investment, is $V(p_1) - V(p_o)$. By the intermediate value theorem, there is exists an intermediate p, $p_o \leq p_M \leq p_1$, that satisfies $[V(p_1) - V(p_o)]/[p_1 - p_o] = V'(p_M) = y(h^*(p_M))$. Since $p_M > p_o$ and both y and h are

$$V[Y(A(S_t'), I_t', E_t') - P_{PE}', A(S_t')] = V[Y(A(S_t), I_t', E_t'), A(S_t)]$$
$$P_{GE} - P_{PE}' = Y(A(S_t), I_t', E_t') - Y(A(S_t), I_t, E_t) \tag{6}$$

If external behaviors were unchanged, then this PE′-GE bias would be negative because, by definition, *I* maximizes the present value of income for *A*(*S*). In general, this bias is smaller than the PE-GE bias.

The PE-GE bias due to external factors cannot be bounded by varying the benchmark behaviors, because there is no presumption that the marginal effects of those behaviors are zero. Instead, estimate of the effects of those behaviors on income are needed.

While expression (5) gives the absolute magnitude of the PE-GE bias, it is useful to analyze its relative magnitude compared to PE valuations of longevity gains, [(P_{GE}- P_{PE})/ P_{PE}].

III. VALUING THE GAINS IN US LONGEVITY, 1900 – 2000: A PARTIAL EQUILIBRIUM CALIBRATION

We develop the infra-marginal framework described above to calibrate the PE value of improvements in US longevity from 1900-2000, a period over which life-expectancy increased by nearly thirty years, from to 48.2 to 77.6. In the formulas above and below, the non-indexed variables correspond to year 1900 and the indexed ones to year 2000. Following Becker, Philipson, and Soares (2005), we calibrate the PE value of life by parameterizing instantaneous utility according to:

$$U(c) = \frac{c^{1-1/\gamma}}{1-1/\gamma} + \alpha \tag{7}$$

where γ is the intertemporal elasticity of substitution and α is a normalization factor that determines the level of annual consumption at which the individual is indifferent between being alive or dead.[4] Under the maintained parameter assumptions on utility, expressions (2) and (3) be can be solved to calculate the *annual* PE willingness to pay for an infra-marginal change in survival from S to S’: [5]

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increasing functions, the GE value of life exceeds the PE value. This example also raises the importance of choosing the correct income, i.e. $y(h^*(p_o))$ when calculating the PE value of life. Choosing an intermediate income, say e.g. $y(h^*(p_M))$, would result in a PE value of life that is incorrectly measured and in this particular case, equal to its GE value.

[4] We assume the following parameter values: intertemporal elasticity of substitution, 1.25; normalization factor α, -16.2 (number has to change); interest rate, 0.03. See Becker, Philipson, and Soares (2005) for a detailed justification of these values.

[5] For more details, see Becker, Philipson, and Soares (2005) and Philipson and Jena (2005). These papers present valuation formulas based on a willingness-to-accept, whereas we calculate the willingness to pay.

$$p_{PE} = y(I,E) - \left[y(I,E)^{1-1/\gamma} \cdot \frac{A(S)}{A(S')} + \alpha \cdot (1-1/\gamma) \cdot \frac{A(S)-A(S')}{A(S')} \right]^{\frac{\gamma}{\gamma-1}} \qquad (8)$$

The corresponding *lifetime* PE willingness to pay, P_{PE}, is simply the discounted sum of the *annual* PE willingness to pay, p_{PE}:

$$P_{PE} = A(\mathbf{S'})\, p_{PE}. \qquad (9)$$

To estimate S and S', we use US cross-sectional survival data from 1900 and 2000 obtained from the Berkeley Mortality Database, which contains historical life-tables published by the Office of the Actuary of the Social Security Administration. For the time being, we assume that *net* income per capita in 1900, *y(I, E)*, equals actual income per capita in that year—that is, we implicitly assume investments in education and health to be zero in the initial period. For an individual earning 1900 income per capita for every year of their life—namely, $4,087 per year in 1996 dollars (Historical Statistics of the United States, 2003)—the calibrated willingness to pay for an improvement in survival from 1900 to 2000 levels is roughly $1,752 per year or $53,010 over a lifetime. As a share of 1900 income per capita, the PE value of these gains in longevity is nearly 43 percent. Murphy and Topel (2006) find that gains in health between 1900 and 2000 range between 10 and 50 percent of annual GDP, so our findings are well within this range.

IV. CALIBRATING THE PE-GE BIAS IN THE VALUE OF LIFE

The size and direction of the PE-GE bias in valuing improvements in longevity are determined by the extent to which changes in survival affect annual income, e.g. through market size effects or incentives for investment. To determine the potential magnitude of these effects, we try several approaches. The first uses the envelope and intermediate theorems briefly discussed in section II to bound the PE-GE bias due to survival-induced changes in internal behaviors alone. The second and third approach turns to the extensive literature documenting the empirical relationship between growth in income per capita, life-expectancy, and population size of the both the working and non-working population. In what follows, we interpret estimates from this literature as identifying the separate causal effects of population and life-expectancy on income. Since income may grow over time for reasons causally unrelated to improvements in longevity, our calibrated effects attempt to isolate the effect of health improvements alone. We use these estimates to calibrate the *counterfactual* increase in annual income from 1900 to 2000 that could be expected given the observed improvements in survival.

A. Using PE to Bound the PE-GS Bias due to Internal Behaviors

We pursue three approaches to quantifying the PE-GE bias. The first evaluates the PE willingness to pay at varying income levels to bound the PE-GE bias *due to internal behaviors alone*. As discussed in Section II, the envelope and intermediate theorems suggest that when 1900 incomes are used to calculate P_{PE}, the calculated value will be less than the GE willingness to pay which accounts for the change in internal behaviors (P_{GE}), and conversely, when the 2000 incomes are used, the calculated value of P_{PE} will be larger than P_{GE}. For some annual income between the 1900 and 2000 values, the calculated value of P_{PE} will be equal to P_{GE}. Thus, one way to bound the PE-GE bias due to internal behaviors is to calculate P_{PE} using the 1900 and 2000 incomes. Figure 1 below shows the calculated values user per-capita income for each year between 1900 and 2000, as well as the P_{PE} share of per-capita income.

FIGURE 1 – CALIBRATED VALUES OF P_{PE} AT VARIOUS INCOME LEVELS

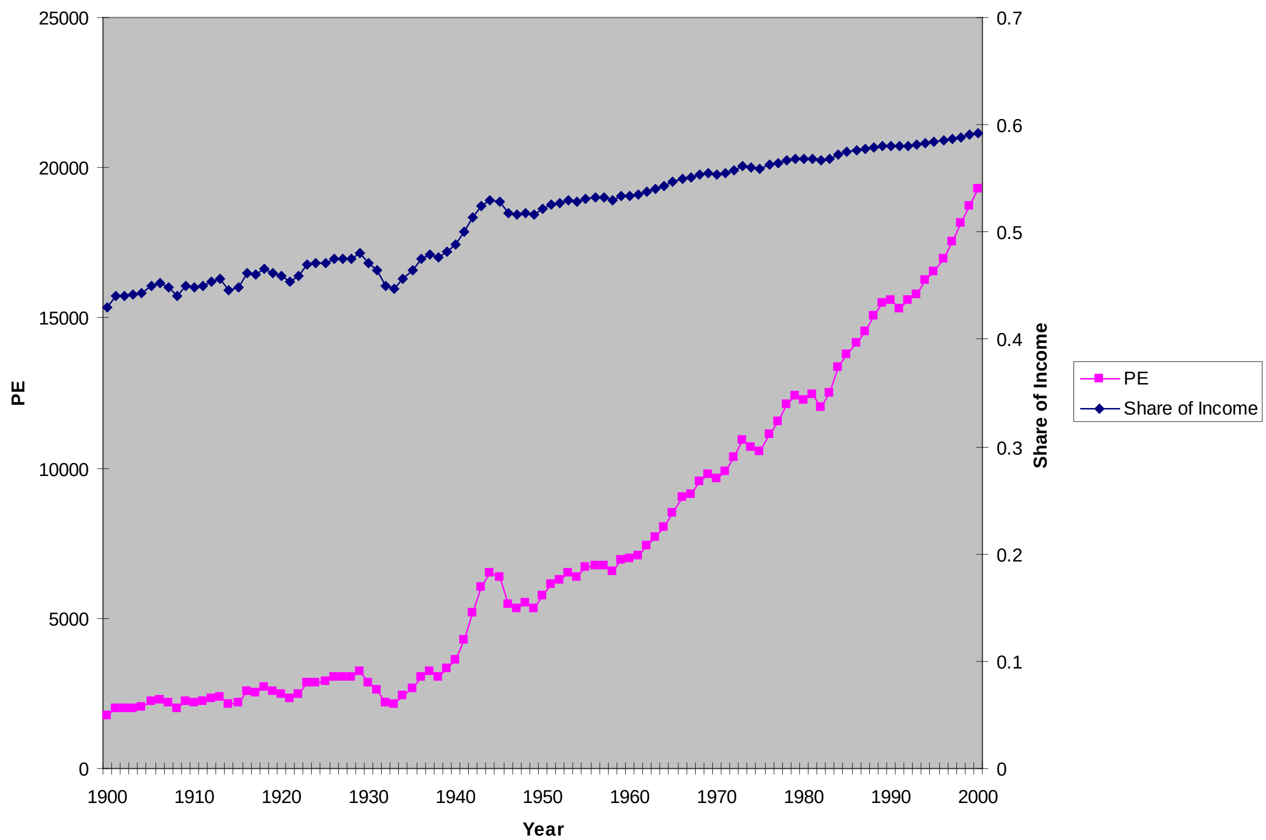


Figure 1 implies that the PE-GE bias due to internal behaviors alone can be potentially very large. Using 1900 incomes, the annual calibrated willingness to pay for an improvement in survival from 1900 to 2000 levels is roughly $1,752 per year. However, when the year 2000 income is used, this amount increases nearly eleven-fold to $19,276 per year. Thus, depending on the income at which it is evaluated, PE can range from $1,752 to $19,276. Typically, the current literature tends to evaluate PE using either the starting (1900) or ending (2000) income. Given that GE lies in between these values, there is potential for the current literature to have significantly under- or over-estimated GE.

B. Framework for Calibrating the PE-GE Bias

In this section, we briefly describe the framework by which we calibrate the counterfactual change in income attributable to the observed changes in survival from 1900-2000. For the time being, we remain agnostic about the effects of such changes on *net income*. While net income rises more slowly than gross income following improvements in survival—because net income adjusts for the increased costs of investment that larger incentives for saving imply—future work will attempt to isolate net income effects from gross income effects. For now, however, we do not distinguish between the two.

Based on the growth literature, our calibrations assume that internal and external behaviors in 1900 affect the *average* annual growth rate of income for l periods, so that

$$y_{2000} = y_{1900} * (1 + lg) \qquad (10)$$

where y_{1900} is income in 1900, and $g = g(I, E)$ is the average annual growth in income that is a function of health related effects. Letting g represent the growth rate under 1900 health and g' the growth rate under 2000 health, we have that the counterfactual increase in income due to changes in health is:

$$y'_{2000} - y_{2000} = y_{1900} * l * (g' - g) \qquad (11)$$

Equation (11) then delivers the *counterfactual* change in 2000 income, $y'_{2000} - y_{2000}$, that could be expected given the health induced change in income growth. This equation can be rewritten as

$$\frac{y'_{2000} - y_{2000}}{y_{1900}} = l * (g' - g) \qquad (12)$$

so that, as a percentage of the initial wages y_{1900} , the increase in wages is proportional to the change in growth rates, as well as the length of time that the increases in growth take effect.

To determine the nature of g, we turn to the extensive literature documenting the empirical relationship between growth in income per capita, life-expectancy, and population size. We perform two sets of calibrations to quantify the PE-GE bias. First, we use estimates from the literature on the effects of population size on income. Second, we use estimates from the literature on the effects of life expectancy on income. Both of these approaches yield calibrated increased in annual income from 1900 to 2000 that could be expected given the observed improvements in survival. In part (C), we discuss the population approach, and in part (D), we discuss the survival approach.

C. Calibrating the PE-GE Bias: Population

The first set of calibrations of the PE-GE bias are based on the estimated effects of population on income, and therefore misses the potential effect of an individual's survival on his own income. Following the literature on population effect, the population-based approach assumes that g is a function of the growth rate of the total and working-age populations, so that:

$$g = g(pop_{total}, pop_{working}) \qquad (13)$$

where pop_{total} is the growth rate of the total population, and $pop_{working}$ is the growth rate of the working age population. To determine the nature of g, we use estimates from the literature, which examines the effect of average annual population growth on economic growth. Typically, this literature estimates regressions of the form

$$g = \gamma_{total} pop_{total} + \gamma_{working} pop_{working} + X\beta + \varepsilon \qquad (14)$$

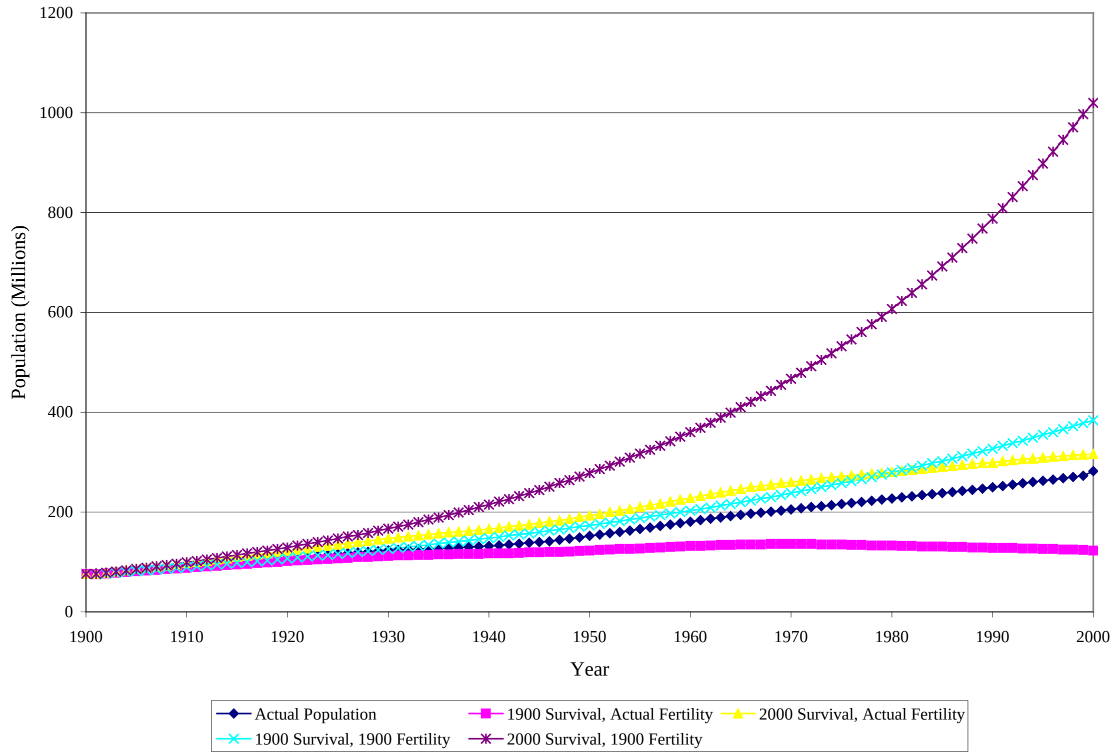
Letting $(pop_{total}, pop_{working})$ and $(pop'_{total}, pop'_{working})$ represent population growth rates under the 1900 and 2000 survival probabilities, the resulting change in annual GDP growth is given by

$$g' - g = \gamma_{total}\left(pop'_{total} - pop_{total}\right) + \gamma_{working}\left(pop'_{working} - pop_{working}\right) \qquad (15)$$

Given estimates of γ_{total} and $\gamma_{working}$ from the literature, equations (14) and (15) can be used to calibrate the change in wages due to population growth. Since we are interested in the period from 1900-2000, we assume that increases in annual population growth last 100 years (l = 100) and affect economic growth for the same period of time.

To use equation (15), we must also determine the growth rates of the total and working age populations under 1900 and 2000 survival rates. Figure 2 depicts how the US population would have evolved under several counterfactual scenarios, all of which are net of the large migration into the US that characterized much of the last century.

FIGURE 2—THE POPULATION EFFECTS OF CHANGES IN SURVIVAL FROM 1900 TO 2000

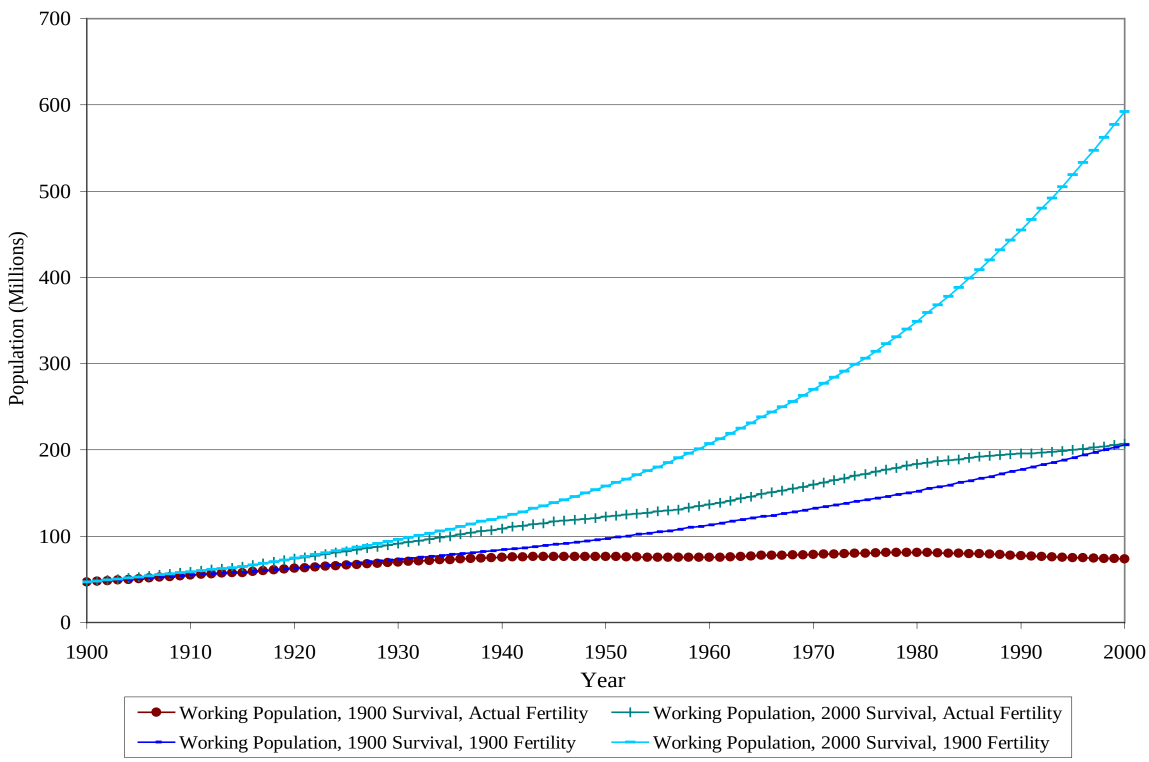


The lowermost curve of Figure 2 depicts the evolution of the US population over time if survival and fertility rates had remained at their 1900 values. In 1900, the US population was 76.1 million persons, and life expectancy was 48 years. With no changes in survival and fertility, the US population would have increased to 336 million by 2000, a percentage gain of 445%. While this number seems large and indeed is greater than the actual US population in 2000, it is important to keep in mind that death *and* fertility rates were higher in 1900, and have fallen over time. To calculate the increase in population due to changes in survival alone, we calculate the change in US population that would have occurred had the survival probabilities in 2000 been in effect in 1900 and fertility rates remained at their 1900 values. The resulting evolution of the US population is the topmost curve in Figure 2, and suggests that the US population would have grown to 1.03 billion by 2000. Our calculations therefore suggest that the US population would have increased by 307% if persons living in the 20th century had enjoyed year 2000 survival.

Rather than hold fertility rates constant from 1900 onwards, an alternative approach would be to allow them to follow their empirically observed time-series. Figure 2 shows how the US population would have evolved if survival were held fixed at 1900 levels and fertility was at its observed rate in each year. The assumptions imply that the US population would have grown to 105 million in 2000. This number is markedly smaller than the population we estimated under constant 1900 fertility, and reflects the fact that fertility rates generally declined over the past century. If survival were held constant at its 2000 levels, the US population would have increased to 316 million by 2000. These calculations suggest that the US population would have increased by 301% if every cohort from 1900 onwards experienced year 2000 survival. Thus, whether or not we allow fertility to change, our estimates suggest that increased survival would have increased the US population by roughly 300%.

Figure 3 below is similar to Figure 2, except that it depicts the evolution of the US working-age population under various survival and fertility probabilities.

FIGURE 3— THE WORKING AGE POPULATION EFFECTS OF CHANGES IN SURVIVAL FROM 1900 TO 2000



In 1900, there were 46.8 million working age persons in the United States. If survival and fertility rates had remained at their 1900 values, this number would have increased to 206 million by 2000. However, if survival and fertility rates in 1900 had been characterized by their 2000 values, there would have been 592 million working age persons in 2000. Thus, the increased survival probabilities would have increased the working age population by 287%. As previously discussed, we also consider the case where fertility rates are allowed to follow their observed time series. In this case, the working age population would have increased to 73.7 million in 2000, under the 1900 survival probabilities and to 207 million, under the 2000 survival probabilities. Therefore, whether or not we allow fertility rates to change, our estimates suggest that the US working age population would have been roughly 280% higher under the year 2000 survival probabilities.

Table 1 shows estimates of $\gamma_{working}$, and γ_{total} from the literature, as well as the implied increases in annual income. To obtain the implied increases in annual income, note that from Figures 2 and 3, the average annual total population growth rate under the 1900 survival probabilities is either 3.2% a year (holding fertility constant at 1900 values) or 0.38% a year (allowing fertility to follow its observed time series). Under the 2000 survival probabilities, the respective values are 12.5% and 3.4%. Thus, the year 2000 survival probabilities increased the annual total population growth rate by either 2.7% or 9.2% depending on our assumptions on fertility. Similar calculations show that improved survival increased the growth rate of the working age population by either 2.8% (allowing fertility to follow the observed time series) or 11.6% (holding fertility constant at its 1900 values).

TABLE 1—Calibrated Effect of Increased Population on Wages, 1900-2000

Study	Coefficient for Total Population Growth Rate (γ_{total})	Coefficient for Working Age Population Growth Rate ($\gamma_{working}$)	% Increase in Annual (fertility constant)	% Increase in Income (time-series fertility)
Bloom, Canning, and Malaney (2000)	-1.3	1.75	834%	139%
Bloom and Malaney (1998)	-0.56	0.46	18.4%	-22.4%
Bloom and Sachs(1998)	-1.01	1.25	520.8%	77.3%
Bloom and Williamson (1998)	-1.03	1.46	746.0%	130.7%
Hamoudi and Sachs (1999)	-1.31	1.95	1056.8%	192.3%

Table 1 shows that population can have potentially large effects on income, and therefore the GE/PE bias. Under the most extreme scenario, income would have been 1057% higher in 2000. Since we estimate that P_{PE} is 43% of income, this implies that the ratio of the GE-PE bias to P_{PE} is 24.6. In general the larger biases are seen under the assumption that survival increases have no effect on fertility. Because our reference period is 1900, a period of high fertility, holding birth rates constant at their 1900 levels means that increases in survival have very large effects on population growth which translates into large effects on income. Under the assumption of constant fertility, the mean increase in income is 635%, implying a GE bias/P_{PE} ratio of 14.8. When the observed fertility rates are used to calculate population, the mean increase in income is 103%, implying a GE bias/P_{PE} ratio of 2.4.

These calibrated biases are usefully contrasted with theory-induced values of the bias. At one Malthusian extreme, suppose that capital is inelastically supplied, that survival does not affect the fraction of the population that is employed, and that aggregate production is Cobb-Douglas with labor share 0.70.[6] In this case, ϕ = -0.30 because the marginal product of labor is proportional to the labor force raised to the -0.30 power. Thus, the Malthusian extreme implies that P_{PE} is *overstated* by a factor of 0.9/0.43 = or 210%. At the other extreme would be the largest positive estimate of the effect of population on per capita income obtained above.

D. Calibrating the PE-GE Bias: Life Expectancy Reduced Form

Our second approach uses the growth literature to calibrate the change in annual income attributable to the observed increase in longevity from 1900 to 2000. This literature includes cross-country regressions of log per-capita income on log life expectancy and other variables. Typically, this literature estimates equations of the form

$$g = \gamma_{LE} * \ln\left(LE\right) + X\beta + \varepsilon \qquad (16)$$

where *LE* represents life expectancy. Equations (16) and (12) imply that the elasticity of income with respect to longevity is simply $\gamma_{LE}*l$. For l, we conservatively assume that changes in life expectancy affect GDP growth for the length of the cross section used in a particular study and have no effects after that time. Thus, γ_{LE} multiplied by the cross-section length is the elasticity of final income with respect to life expectancy, ε. For example, Barro (1996) estimates that γ_{LE} equals 0.042; a 1% increase in life expectancy increases annual GDP by 0.042%. Since Barro uses a 10 year cross section, the elasticity over that period is $\varepsilon = 10\cdot 0.42 = 0.42$; a 1% increase in life expectancy increases per-capita GDP by 0.42%. Given that life expectancy increased by 161% between 1900 and 2000, the percentage increase in annual income owing to life expectancy is 1.61ε. Since we estimate the P_{PE} is 43% of initial income, we have that $1.61\varepsilon/0.43$ is the size of the GE bias relative to P_{PE}.

Table 2 below reports values of γ_{LE} and ε from several studies in the growth literature. In addition, the Table reports whether the studies controlled for population. Recall that changes in life expectancy may increase income via aggregate effects (e.g. through population) or individual effects (through human capital accumulation or savings incentives). Some of these regressions do not include population. Therefore, assuming all other determinants of per capita income are either held constant or uncorrelated with life expectancy, the life expectancy coefficient can be interpreted as a total effect of aggregate and individual life expectancy. In those regressions including population growth as a control, the life expectancy coefficient can be interpreted as the effect of individual life expectancy. In general, there appears to be little consensus in the growth

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[6] The second assumption may be unwarranted if changes in survival alter the demographic composition of the population (e.g. by increasing the fraction of elderly through improvements in end-of-life care) so that labor supply is not raised proportionately with population.

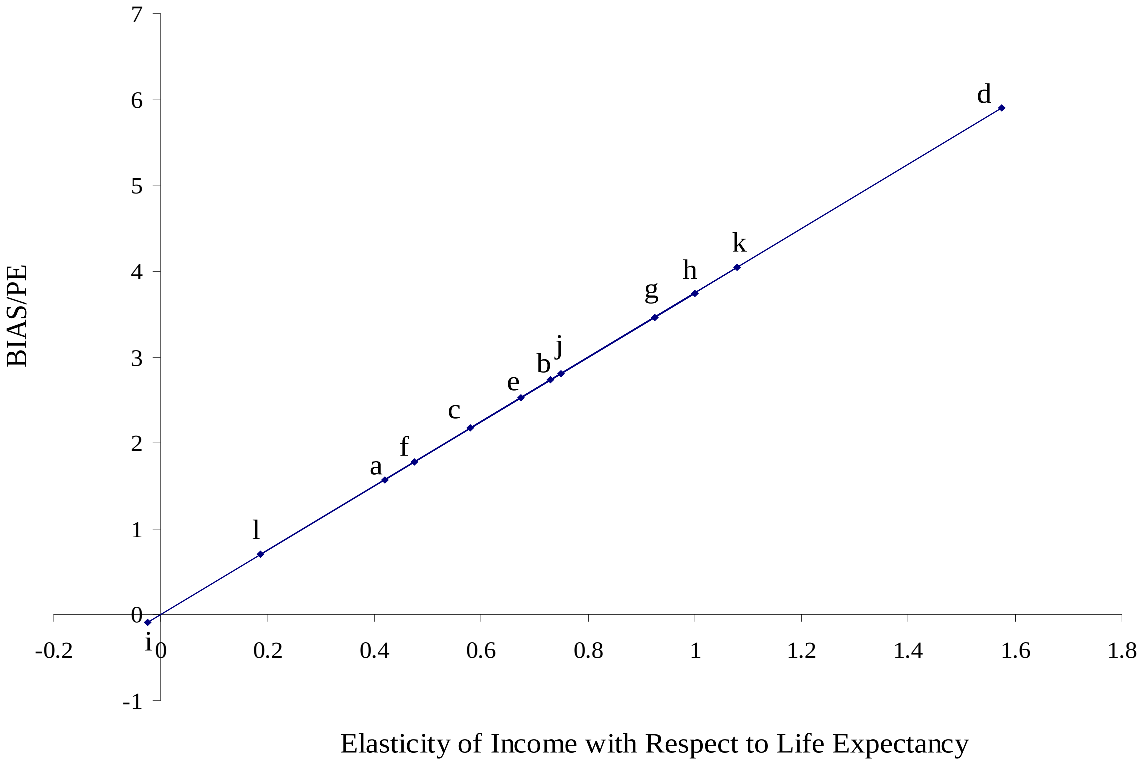
literature on the precise effect of life expectancy on GDP, as ε varies from -0.025 to 1.575. In general, however, most studies find that increases in life expectancy lead to increases in income per capita.

TABLE 2—Calibrated Effect of Increased US Life Expectancy on Income, 1900-2000

		Log Life-Expectancy Coefficient in Growth Regressions (γ)	Length of Cross Section (years)	Elasticity of Final Annual Income with Respect to Life Expectancy (ε)	Control for Population?
(a)	Barro (1996)	0.042	10	0.42	No
(b)	Barro and Lee (1994)	0.073	10	0.73	No
(c)	Barro and Sala-i-Martin (1995)	0.058	10	0.58	No
(d)	Bloom, Canning, and Malaney (2000)	0.063	25	1.575	Yes
(e)	Bloom and Malaney (1998)	0.027	25	0.675	Yes
(f)	Bloom et al. (1999)	0.019	25	0.475	Yes
(g)	Bloom and Sachs (1998)	0.037	25	0.925	Yes
(h)	Bloom and Williamson (1998)	0.04	25	1.00	Yes
(i)	Casselli et al. (1996)	-0.001	25	-0.025	No
(j)	Gallup and Sachs (2000)	0.03	25	0.75	No
(k)	Hamoudi and Sachs (1999)	0.072	15	1.08	Yes
(l)	Sachs and Warner (1997)	0.0075	25	0.1875	Yes

Given the calibrated income effects above, Figure 4 plots the relationship between the relative bias in the PE value of life (i.e. $[P_{GE} - P_{PE}]/P_{PE}$) and the elasticity of annual income with respect to life-expectancy.

FIGURE 4—PE-GE Bias in the Value of Survival Gains: United States, 1900-2000



Notes: (a) Barro (1996); (b) Barro and Lee (1994); (c) Barro and Sala-i-Martin (1995); (d) Bloom, Canning, and Malaney (2000); (e) Bloom and Malaney (1998); (f) Bloom et al. (1999); (g) Bloom and Sachs (1998); (h) Bloom and Williamson (1998); (i) Caselli et al. (1996); (j) Gallup and Sachs (2000); (k) Hamoudi and Sachs (1999) (l) Sachs and Warner (1997)

Several points stand out in Figure 4. First, the calibrated PE-GE bias in the value of life from 1900 to 2000 is potentially large, with the most extreme estimate suggesting a bias six times as large the corresponding PE value. This estimate implies that the increase in annual income attributable to the observed improvement in longevity is six times larger than the willingness to pay for the improvement in survival alone. Second, the calibrated effects predicted by the studies surveyed show no clear consensus.[7] Estimates of the bias range from being slightly negative to four to six times as high as the PE value of life. Despite the variation in our calibrated effects, it appears that the majority of the studies predict PE-GE biases on the order of two to four times the PE value of life.

[7] This lack of consensus is in part due to differences in the estimated effects of life-expectancy on average, annual GDP growth, β. It is also due to variation across studies in the length of time considered. For example, consider two studies that estimate an elasticity of average, annual growth with respect to life expectancy of 1. If Study 1 spans a ten-year period, while Study 2 spans a twenty-year period, the calibrated effect on final annual income will be twice as large in the second study, simply because the growth in income is observed to occur over a longer period of time.

V. CONCLUDING REMARKS

Perhaps the most important change of the last century was the great expansion of life itself. In fact, recent estimates for the US have demonstrated that the value of gains in longevity have nearly equaled gains in all other material well-being. While these estimates are large by any means, they have typically ignored the important demographic and economic consequences such aggregate changes in longevity can induce. For example, a variety of previous literatures have shown that life expectancy affects individual behavior and that population or scale matters for economic performance. The purpose of our paper is to illustrate the implications of these previous results for valuing the enormous gains in life that took place in the last century, and to make a first attempt at quantifying some of them. Living to age 70 rather than age 40 is not just a 30 year extension in life, but also affects how well one lives their first 40 years as well as their last 30. Living with others who live 70 years is different than living with others who live only 40. We began to quantify the total value of life extension by focusing on two factors linked to life extension: own human capital accumulation and total population. The value of these responses may be on the same order of magnitude – perhaps even larger – than the value of extra life-time itself.

One reason to calculate the benefits of life extension is for the purpose of a cost-benefit analysis of medical research (Murphy and Topel, 2003). However, a cost-benefit analysis that includes the value of the indirect effects of life extension may implicitly propose oblique solutions to problems that could be solved more directly. Suppose, for example, that life extension raises the corporate capital stock, and that the social value of the corporate capital stock exceeds its private value as a consequence of corporate taxation. Then, life extension would have the beneficial side effect of raising the corporate capital stock, but to use this as an argument for medical research amounts to arguing that lives should be extended in order to alleviate damage done by the corporate tax system. Obviously, the more direct solution to that damage is to fix the corporate tax code itself. This is one important reason that we have focused on a particular category of the external effects of life expectancy: those associated with population. Extending lives may well be one of the best and most direct ways of increasing the population.

Theory and empirical studies have cited both beneficial and deleterious effects of population. One conclusion of our paper is that it matters exactly how beneficial or deleterious population may be, because even minor effects in either direction have a big impact on the estimated value of life. However, given the observation that much of R&D has a social return that exceeds its private return, and given that so many people have chosen big cities as their place to live and work, we suspect that the beneficial effects of population are the dominant ones. In this case, the general equilibrium value of life is about three times as much as the partial equilibrium value.

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