Life and Growth

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Some technologies save lives—new vaccines, new surgical techniques, safer highways. Others threaten lives—pollution, nuclear accidents, global warming, and the rapid global transmission of disease. How is growth theory altered when technologies involve life and death instead of just higher consumption? This paper shows that taking life into account has first-order consequences. Under standard preferences, the value of life may rise faster than consumption, leading society to value safety over consumption growth. As a result, the optimal rate of consumption growth may be substantially lower than what is feasible, in some cases falling all the way to zero.

I. Introduction

Some technologies save lives—new vaccines, new surgical techniques, safer highways. Others threaten lives—pollution, nuclear accidents, global warming, the rapid global transmission of disease, and bioengineered viruses. How is growth theory altered when technologies involve life and death instead of just higher consumption?

To begin, consider what might be called a "Russian roulette" theory of economic growth. Suppose the overwhelming majority of new ideas are

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beneficial and lead to growth in consumption. However, there is a small chance that a new idea will be dangerous and cause substantial loss of life. Do discovery and economic growth continue forever in such a framework, or should society eventually decide that consumption is high enough and stop playing the game of Russian roulette? How is this conclusion affected if researchers can also develop lifesaving technologies?

This paper shows that taking life and death into account has first-order consequences. The answers to these questions depend crucially on the shape of preferences. For a large class of conventional specifications, including log utility, the value of life rises faster than consumption, leading society to value safety over consumption growth. As a result, the optimal rate of consumption growth may be substantially lower than what is feasible, in some cases falling all the way to zero.

This project builds on a diverse collection of papers. Murphy and Topel (2003), Nordhaus (2003), and Becker, Philipson, and Soares (2005) emphasize a range of economic consequences of the high value attached to life. Murphy and Topel (2006) extend this work to show that the economic value of future innovations that reduce mortality is enormous. Weisbrod (1991) early on emphasized that the nature of health spending surely influences the direction and rate of technical change. Hall and Jones (2007)—building on Grossman (1972) and Ehrlich and Chuma (1990)—is a direct precursor to the present paper, in ways that will be discussed in detail below.[1]

The paper is organized as follows. Section II presents a simple version of the "Russian roulette" model outlined above. The model is interesting in its own right, but it also serves to introduce the key role that the value of life and the shape of preferences play in the analysis. A limitation of this framework is that it does not recognize that technological change arguably reduces mortality more than it increases it. Section III therefore develops a richer model that features both "standard" ideas that raise consumption and "lifesaving" ideas that reduce mortality. This framework allows the growth rate to vary continuously, permitting a careful study of the mechanisms highlighted in the simple model. Section IV discusses a range of empirical evidence that is helpful in judging the relevance of these results. Section V presents a calibration of the consumption growth slowdown and a numerical example illustrating that the asymptotic results of the theory have similar implications for the transition path. Section VI presents conclusions.

[1] Other related papers take these ideas in different directions. Acemoglu and Johnson (2007) estimate the causal impact of changes in life expectancy on income. Malani and Philipson (2011) provide a careful analysis of the differences between medical research and research in other sectors. Dalgaard and Strulik (2014) model aging as the accumulation of "deficits" and consider how this process can be slowed by health spending.

II. The Russian Roulette Model

A "Russian roulette" model of growth allows us to see some of the main issues in this paper in the clearest way. Suppose the overwhelming majority of new ideas are beneficial and lead to consumption growth. However, there is a small chance that research will result in a disaster that kills some fraction of the population. What does growth look like in this setting?

In the economy, a single agent is born at the start of each period and lives for at most one period. The agent is endowed with some initial stock of knowledge that generates a consumption level c and has a utility function $u(c) = \bar{u} + [c^{1-\gamma}/(1-\gamma)]$. The parameter $\bar{u}$ is a constant that will be discussed in more detail below.

The only decision faced by the agent is whether or not to conduct research. With some (high) probability $1 - \pi$, research leads to a new idea that increases consumption by the growth rate $\bar{g}$. With some small probability π, however, the research results in a disaster that kills the agent.[2] We are free to normalize the utility associated with death to any value and therefore choose zero. Finally, if there is no research, consumption remains constant at the level associated with the original stock of knowledge and there is no risk of a disaster.

Expected utility for the two options "Research" and "Stop" is given by

$$U^{\text{Research}} = (1-\pi)u(c_1) + \pi \cdot 0 = (1-\pi)u(c_1), \;\; c_1 = c(1+\bar{g}),$$
$$U^{\text{Stop}} = u(c).$$

The agent engages in research if $U^{\text{Research}} > U^{\text{Stop}}$. This condition is itself amenable to analysis, but more intuition is available—intuition that sheds light on the richer model I present later—if we take a first-order Taylor expansion around $u(c)$. Using the approximation $u(c_1) \approx u(c) + u'(c) \cdot (c_1 - c) = u(c) + u'(c)\bar{g}c$, the agent chooses to undertake research if

$$(1-\pi)u'(c)\bar{g}c > \pi u(c).$$

This expression has a nice interpretation: the left side is the benefit of engaging in research and the right side is the cost. For the benefit, with probability $1 - \pi$ the research is successful and increases consumption by the amount $\bar{g} \cdot c$, which gets converted into utility units by the conversion factor $u'(c)$. On the cost side, with probability π, the research ends in failure and the utility flow $u(c)$ never gets to be enjoyed.

[2] Extending the model to include a population of representative agents, there is an equivalence in this setup between a fraction π of the existing population dying and the entire population facing a probability π of extinction. Both interpretations are useful.

Rearranging this expression, research occurs as long as

$$\bar{g} > \frac{\pi}{1-\pi} \cdot \frac{u(c)}{u'(c)c}. \tag{1}$$

Because $\bar{g}$ and π are both parameters, the key variable in this expression is the term $u(c)/u'(c)c$. This term has a natural economic interpretation: $u(c)$ is the value of life in utils, and dividing by $u'(c)$ converts this into consumption units. Therefore, this term is the value of life as a ratio to the level of consumption.

With $u(c) = \bar{u} + [c^{1-\gamma}/(1-\gamma)]$, this value of life expression is

$$\frac{u(c)}{u'(c)c} = \bar{u}c^{\gamma-1} + \frac{1}{1-\gamma}. \tag{2}$$

It turns out to be convenient to analyze three cases separately: $\gamma < 1$, $\gamma > 1$, and log utility ($\gamma = 1$).

A. *Exponential Growth: 0 < γ < 1*

To begin, let us assume $\gamma < 1$ and set $\bar{u} = 0$, as this parameter does not play a crucial role in this case. With these parameter restrictions, the value of life relative to consumption in (2) is constant and equal to $1/(1-\gamma)$. Substituting back into (1), research continues forever as long as $\bar{g}$ is sufficiently large relative to the probability of a research disaster. In this case, the economy will grow exponentially across generations, apart from rare disasters. Of course, each generation is also taking a risk, and occasionally a research disaster kills off a generation before they can enjoy the utility associated with consumption.[3]

B. *The End of Growth: γ > 1*

With $\gamma > 1$, the constant $\bar{u}$ plays an essential role. In particular, recall that I have normalized the utility associated with "death" to be zero: the individual gets $u(c)$ if she lives and gets zero if she dies. But this means that $u(c)$ must be greater than zero for life to be worth living. Otherwise, death is preferred to life. With $\gamma > 1$, however, $c^{1-\gamma}/(1-\gamma)$ is less than zero. For example, this flow is $-1/c$ for $\gamma = 2$. An obvious way to make our problem interesting is to add a positive constant to flow utility, and this motivates the introduction of $\bar{u}$, which represents the upper bound for utility.[4]

[3] Without using the Taylor series approximation, the exact condition for research to continue is $(1-\pi)(1+\bar{g})^{1-\gamma} > 1$. If one allows for $\bar{u} > 0$, then the value of life relative to consumption is initially even higher but then falls asymptotically to $1/(1-\gamma)$, so the same conditions apply.

[4] There exists a value of consumption below which flow utility is still negative. Below this level, individuals would prefer death to life; see Rosen (1988). This level is very low for plau-

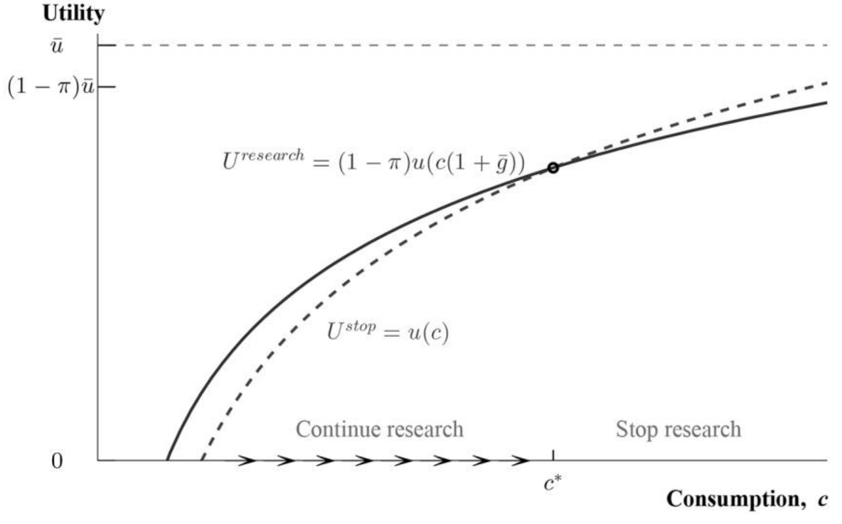

FIG. 1.—The research decision when $\gamma > 1$. As long as consumption is less than c^*, each generation engages in research. Once consumption reaches (or exceeds) c^*, even a tiny risk of a research disaster is not worth taking because life becomes too valuable. Color version available as an online enhancement.

Assuming $\gamma > 1$ and $\bar{u} > 0$, notice that the value of life relative to consumption in equation (2) increases with consumption. That is, as each generation gets richer, life becomes increasingly valuable relative to consumption. Substituting this expression back into the research choice in equation (1) then leads to the following result: When consumption is small, each generation chooses to engage in research. However, eventually society becomes sufficiently rich that the gains from higher consumption growth are outweighed by the risks of a disaster and economic growth comes to an end.

Without making the Taylor series approximation, this choice can be illustrated graphically, as in figure 1, and the same basic conclusion follows: once society reaches (or exceeds) consumption level c^*, no additional research is undertaken and growth stops.

C. Log Utility

The case of log utility is more subtle. In contrast to the case of $\gamma > 1$, flow utility is unbounded in the log case. However, it turns out that growth

sible parameter values and can be ignored here. The role of the constant in flow utility is also discussed by Murphy and Topel (2003), Nordhaus (2003), Becker et al. (2005), and Hall and Jones (2007).

eventually ceases in this case as well. The value of life expression in the log case is $u(c)/u'(c)c = \bar{u} + \log c$. So even in this case the value of life rises relative to consumption and the condition in (1) for research to continue is eventually violated.[5]

D. *Summary of the Russian Roulette Model*

The simple model illustrates that a key consideration in the trade-off between safety and consumption growth is the value of life relative to consumption. If the value of life rises more slowly than consumption ($\gamma < 1$), then safety considerations fade in importance and growth continues forever. However, if the value of life rises faster than consumption, safety considerations become increasingly important over time and can eventually lead to a cessation of research and consumption growth.

III. Life and Growth in a Richer Setting

The Russian roulette model in the previous section is elegant and delivers intuitive results for the interaction between safety and growth. However, that setup ignores the important possibility that research can make the world safer rather than more dangerous. Medical innovations, antilock brakes, and autopilots for airplanes are examples of technologies that save lives rather than endanger them. The simple model also treats growth as a "black box."

In this section, I address these concerns by adding safety considerations to a standard growth model based on the discovery of new ideas. The result deepens our understanding of the interactions between safety and growth. For instance, in this framework, concerns for safety can slow the rate of consumption growth (e.g., from 4 percent to 1 percent) but will never lead to a steady-state level of consumption. The model also highlights the distinction between GDP growth and consumption growth: here, it is only the latter that is affected.

The model below can be viewed as combining the "direction of technical change" work by Acemoglu (2002) with the health spending model of Hall and Jones (2007). That is, I posit a standard idea-based growth model in which there are two types of ideas instead of one: ideas that enhance consumption and ideas that save lives. The key allocative decisions in the economy are (i) how many scientists to put into the consumption versus lifesaving sectors and (ii) how many workers to put into using these ideas to manufacture goods.

[5] Without taking the Taylor approximation, we get the same result: the condition for research to continue is $(1 - \pi)\log(1 + \bar{g}) > \pi(\bar{u} + \log c)$.

A. The Economic Environment

The economy features two main sectors, a consumption sector and a lifesaving sector. On the production side, both sectors are quite similar, and each looks very much like the Jones (1995) version of the Romer (1990) growth model. In fact, I will purposefully make the production side of the two sectors as similar as possible (i.e., using the same parameters) so it will be clear where the results come from.

Total production of the consumption good C_t and the lifesaving good H_t are given by

$$C_t = \left[\int_0^{A_t} x_{it}^{1/(1+\alpha)}\,di\right]^{1+\alpha} \quad \text{and} \quad H_t = \left[\int_0^{B_t} z_{it}^{1/(1+\alpha)}\,di\right]^{1+\alpha}. \tag{3}$$

Each sector uses a variety of intermediate goods to produce output with the same basic production function. The main difference is that different varieties—different ideas—are used for each sector: A_t represents the range of technologies available to produce consumption goods, while B_t represents the range used to produce lifesaving goods. It might be helpful to think of the z_{it} as purchases of different types of pharmaceuticals and surgical techniques. But I have in mind a broader category of goods as well, such as pollution scrubbers in coal plants, seatbelts and airbags, child safety locks, lifeguards at swimming pools, and warning labels on cigarettes.

Once the blueprint for a variety has been discovered, one unit of labor can be used to produce one unit of that variety. The number of people working as labor is denoted L_t, so the resource constraint for this labor is

$$\underbrace{\int_0^{A_t} x_{it}\,di}_{\equiv L_{ct}} + \underbrace{\int_0^{B_t} z_{it}\,di}_{\equiv L_{ht}} \leq L_t. \tag{4}$$

People can produce either goods, as above, or ideas. When they produce ideas, we call them scientists, and the production functions for new ideas are given by

$$\dot{A}_t = S_{at}^{\lambda} A_t^{\phi} \quad \text{and} \quad \dot{B}_t = S_{bt}^{\lambda} B_t^{\phi}, \tag{5}$$

where I assume $\phi < 1$. Once again, notice that I assume the same parameters for the idea production functions in the two sectors; this assumption could be relaxed but is useful because it helps to clarify where the main results come from.

The resource constraints on scientists and people more generally are

$$S_{at} + S_{bt} \leq S_t \tag{6}$$

and

$$S_t + L_t \leq N_t. \tag{7}$$

That is, N_t denotes the total number of people, who can work as scientists or labor. In turn, scientists and labor can work in either the consumption sector or the lifesaving sector.

Next, consider mortality. Individuals face a time-varying mortality rate δ_t. The probability that an agent born at date 0 survives to date t is given by

$$M_t = e^{-\int_0^t \delta_s ds}.$$

Equivalently, the law of motion for this survival probability is

$$\dot{M}_t = -\delta_t M_t, \quad M_0 = 1. \tag{8}$$

The mortality rate is endogenous and can be reduced by purchasing lifesaving goods. An individual who purchases $h_t \equiv H_t/N_t$ faces a mortality rate

$$\delta_t = h_t^{-\beta}. \tag{9}$$

Expected lifetime utility, taking mortality into account, is then

$$U = \int_0^\infty e^{-\rho t} u(c_t) M_t dt. \tag{10}$$

See Arthur (1981), Rosen (1988), and Murphy and Topel (2006) for similar formulations of expected utility with time-varying mortality.

As discussed earlier, I specify flow utility as

$$u(c_t) = \bar{u} + \frac{c_t^{1-\gamma}}{1-\gamma}, \quad c_t \equiv C_t/N_t. \tag{11}$$

Flow utility takes a standard form, augmented by a constant $\bar{u}$, which is related to the overall value of life versus death.[6]

Finally, for population growth, there are two relatively natural ways to proceed. One can assume exogenous fertility so that reductions in mortality raise population growth. Alternatively, one can assume that fertility adjusts so that the rate of population growth is exogenously constant. It turns out that the main results go through in either case. I assume the latter here, so that population growth occurs at a constant positive rate:[7]

$$\dot{N}_t = \bar{n} N_t. \tag{12}$$

[6] As usual, ρ must be sufficiently large given growth so that utility is finite.

[7] The working paper version in Jones (2011) considers the former case.

B. *Allocating Resources*

This economic environment features 14 unknowns—C_t, H_t, c_t, h_t, A_t, B_t, x_{it}, z_{it}, S_{at}, S_{bt}, S_t, L_t, M_t, δ_t—and 11 equations—equations (3)–(9), together with the definitions for h_t and c_t (I am not counting lifetime utility, flow utility, and the exogenous population process in this numeration).

There are, not surprisingly then, three key allocative decisions that have to be made in the economy, summarized by three allocative fractions s_t, ℓ_t, and σ_t:

1. How many scientists make consumption ideas versus lifesaving ideas: $s_t \equiv S_{at}/S_t$.
2. How many workers make consumption goods versus lifesaving goods: $\ell_t \equiv L_{ct}/L_t$. (Given the symmetry of the setup, it is efficient to allocate the x_{it} and the z_{it} symmetrically across varieties, so I will just impose this throughout the paper to simplify things.)
3. How many people are scientists versus workers: $\sigma_t \equiv S_t/N_t$.

C. *A Rule of Thumb Allocation*

For reasons that will become clear, it is convenient to begin with a simple "rule of thumb" allocation, analogous to Solow's assumption of a fixed saving rate in his version of the neoclassical growth model.

In particular, consider the following *rule of thumb allocation*: $s_t = \bar{s}$, $\ell_t = \bar{\ell}$, and $\sigma_t = \bar{\sigma}$, where each of these new parameters is between zero and one. That is, consider putting a fixed fraction of the scientists in each research sector and a fixed fraction of the workers in each goods sector, and let a fixed fraction of the population work as scientists.

It is straightforward to show the following result.

Proposition 1 (BGP under the rule of thumb allocation). Under the rule of thumb allocation, where $s_t = \bar{s}$, $\ell_t = \bar{\ell}$, and $\sigma_t = \bar{\sigma}$, all between zero and one, there exists a balanced growth path (BGP) such that

$$g_A^* = g_B^* = \frac{\lambda \bar{n}}{1-\phi}, \tag{13}$$

$$g_c^* = g_h^* = \alpha g_A^* = \alpha g_B^* = \bar{g} \equiv \frac{\alpha \lambda \bar{n}}{1-\phi}, \tag{14}$$

and

$$g_\delta^* = -\beta \bar{g}, \;\; \delta_t \to 0. \tag{15}$$

This is basically the expected outcome in a growth model of this flavor. With labor allocated symmetrically within the consumption and life sectors, the production functions are $C_t = A_t^\alpha L_{ct}$ and $H_t = B_t^\alpha L_{ht}$. Notice that each production function exhibits increasing returns to scale measured by α, reflecting the nonrivalry of both kinds of ideas. The idea production functions are also symmetric in form. For instance, $\dot{A}_t/A_t = S_{at}^{\lambda}/A_t^{1-\phi}$. So along a BGP, S_{at}^{λ} and $A_t^{1-\phi}$ must grow at the same rate. Since the growth rate of scientists is pinned down by the population growth rate, this means that the growth rate of A_t (and B_t) will be as well. Therefore, B_t goes to infinity, which means that the mortality rate δ_t falls to zero, and so on.

The rule of thumb allocation suggests that this model will deliver a BGP with ever-increasing life expectancy. Moreover, growth is balanced in a particular way: technical change occurs at the same rate in both the consumption and life sectors, so the relative price of the consumption and life aggregates is constant. And by assumption, a constant fraction of labor and scientists work in each sector. Of course, I could have altered some of these results simply by making the elasticity of substitution or the parameters of the idea production function differ between the two sectors. But that is not where I wish to go. For the moment, simply note that everything is nicely behaved and straightforward in the rule of thumb allocation.

D. The Optimal Allocation

Somewhat surprisingly, the rule of thumb allocation turns out not to be a particularly good guide to the dynamics of the economy under the optimal allocation. Instead, as suggested by the Russian roulette model at the start of this paper, there is a sense in which consumption growth is slower than what is feasible because of a shift in the allocation of resources when diminishing returns to consumption are sufficiently strong.

There are many interesting questions related to welfare theorems in this type of model: is a decentralized market allocation efficient? One can imagine various externalities related to safety, particularly when "existential" risks are under consideration. For now, however, I put these interesting questions aside. My concern instead is with how safety considerations affect the economy even when resources are allocated optimally.

The *optimal allocation* of resources is a time path for c_t, h_t, s_t, ℓ_t, σ_t, A_t, B_t, M_t, δ_t that maximizes the utility of a representative agent, solving the following problem:

$$\max_{\{s_t,\ell_t,\sigma_t\}} U = \int_0^{\infty} M_t u(c_t) e^{-\rho t} dt \tag{16}$$

subject to

$$c_t = A_t^{\alpha} \ell_t (1 - \sigma_t), \tag{17}$$

$$h_t = B_t^\alpha(1-\ell_t)(1-\sigma_t), \tag{18}$$

$$\dot{A}_t = s_t^\lambda \sigma_t^\lambda N_t^\lambda A_t^\phi, \tag{19}$$

$$\dot{B}_t = (1-s_t)^\lambda \sigma_t^\lambda N_t^\lambda B_t^\phi, \tag{20}$$

$$\dot{M}_t = -\delta_t M_t, \;\; \delta_t = h_t^{-\beta}. \tag{21}$$

Note that other definitions of "optimal" are possible here; for example, the representative agent here does not care about future generations. The results below would continue to hold even with altruistic individuals or with a social welfare function that puts weight on future generations. The "selfish" approach here illustrates that none of the results come from these additional considerations.[8]

To solve for the optimal allocation, I define the Hamiltonian:

$$\mathcal{H} = M_t u(c_t) + p_{at} s_t^\lambda \sigma_t^\lambda N_t^\lambda A_t^\phi + p_{bt}(1-s_t)^\lambda \sigma_t^\lambda N_t^\lambda B_t^\phi - v_t \delta_t M_t, \tag{22}$$

where $c_t = A_t^\alpha \ell_t(1-\sigma_t)$ and $\delta_t = h_t^{-\beta} = [B_t^\alpha(1-\ell_t)(1-\sigma_t)]^{-\beta}$. The costate variables—$p_{at}$, p_{bt}, and v_t—capture the shadow values of an extra consumption idea, an extra lifesaving idea, and an extra lifetime (resetting M to one) to maximized welfare.

Using the maximum principle and solving the first-order necessary conditions for the optimal allocation, we can derive several results. The most important of these is given in the next proposition (proofs are relegated to App. A).[9]

Proposition 2 (Optimal growth with $\gamma > 1 + \beta$). Assume that the marginal utility of consumption falls rapidly, in the sense that $\gamma > 1 + \beta$. Then the optimal allocation features an asymptotic constant growth path such that as $t \to \infty$, the fraction of labor working in the consumption sector ℓ_t

[8] For example, one could multiply flow utility by the size of the population N_t in eq. (16) to include weight on future generations, but this is essentially equivalent to changing the rate of time preference.

[9] The argument that these first-order conditions characterize the solution is more subtle than usual. The standard very stringent Arrow/Mangasarian conditions for concavity do not hold for this problem, nor even for Jones (1995) (despite the fact that they hold for Romer [1990]!). However, Romer (1986) developed a different approach for growth models with increasing returns, and that approach works here: one can use the arguments in Romer (1986) to show that there exists a solution to this problem and show that it is interior. Since the first-order conditions characterize any interior solution and they identify a unique path here, it must indeed be the solution.

and the fraction of scientists making consumption ideas s_t both fall to zero at constant exponential rates, and asymptotic growth is given by[10]

$$g_s^* = g_\ell^* = \frac{-\bar{g}\,(\gamma - 1 - \beta)}{1 + (\gamma - 1)\left(1 + \dfrac{\alpha\lambda}{1-\phi}\right)} < 0, \quad \bar{g} \equiv \frac{\alpha\lambda\bar{n}}{1-\phi}, \tag{23}$$

$$g_A^* = \frac{\lambda(\bar{n} + g_s^*)}{1-\phi}, \quad g_B^* = \frac{\lambda\bar{n}}{1-\phi} > g_A^*, \tag{24}$$

$$g_\delta^* = -\beta\bar{g}, \quad g_h^* = \bar{g}, \tag{25}$$

$$g_c^* = \alpha g_A^* + g_\ell^* = \bar{g} \cdot \frac{1 + \beta\left(1 + \dfrac{\alpha\lambda}{1-\phi}\right)}{1 + (\gamma - 1)\left(1 + \dfrac{\alpha\lambda}{1-\phi}\right)} < \bar{g}. \tag{26}$$

This proposition echoes the key result from the Russian roulette model at the start of the paper: if the marginal utility of consumption runs into sufficiently sharp diminishing returns, safety considerations alter the essential nature of optimal growth. While in the earlier setup it was possible for consumption growth to cease, the model given here displays a more subtle result.

First, the economy optimally settles down to an asymptotic constant growth path (one in which all variables grow at constant rates). However, along this path, consumption grows at a rate that is slower than what is feasible. This can be seen by comparing the consumption growth rates for the rule of thumb allocation in (14) and the optimal allocation in (26): when $\gamma - 1 > \beta$, $g_c^* < \bar{g}$.

Second, the proximate cause of this slower growth is an exponential shift in the allocation of resources. Both the fraction of scientists and the fraction of workers engaged in the consumption sector—s_t and ℓ_t—fall exponentially over time along the BGP.

To see how this shift slows growth, recall the production functions for ideas, writing them as follows:

$$\frac{\dot{B}_t}{B_t} = \frac{(1 - s_t)^\lambda \sigma_t^\lambda N_t^\lambda}{B_t^{1-\phi}} \quad \text{and} \quad \frac{\dot{A}_t}{A_t} = \frac{s_t^\lambda \sigma_t^\lambda N_t^\lambda}{A_t^{1-\phi}}.$$

The share $1 - s_t$ in the lifesaving sector converges to one, leading to the expected result for g_B: since σ_t is also constant asymptotically, a con-

[10] These results, and indeed the results throughout the remainder of this paper, have the following form: $\lim_{t\to\infty} g_{ct} = g_c^*$, and so on.

stant value of $\dot{B}_t/B_t$ requires N_t^λ and $B_t^{1-\phi}$ to grow at the same rate; therefore, $g_B^* = \lambda\bar{n}/(1-\phi)$. In contrast, the share s_t in the consumption ideas production function falls exponentially toward zero. The exponential shift of scientists out of this sector means that a constant $\dot{A}_t/A_t$ occurs if and only if $s_t^\lambda N_t^\lambda$ and $A_t^{1-\phi}$ grow at the same rates. But in this case, the shift of scientists out of the consumption sector leads the numerator to grow more slowly than $\lambda\bar{n}$, leading to $g_A^* = \lambda(g_s^* + \bar{n})/(1-\phi)$. The negative trend in s_t slows growth in A_t relative to what is feasible with a constant allocation of scientists.

This result makes a clear prediction: we should see the composition of research shifting over time away from consumption ideas and toward lifesaving ideas if the model is correct and if the marginal utility of consumption falls sufficiently fast. I will provide empirical evidence on this prediction later in the paper.

To understand the fundamental cause for this structural change in the economy, consider the following equation, which is the first-order condition for allocating labor between the consumption and life sectors:

$$\frac{1-\ell_t}{\ell_t} = \beta\frac{\delta_t v_t}{u'(c_t)c_t}. \tag{27}$$

The left side of this equation is just the ratio of labor working in the life sector to labor working in the consumption sector. This equation says that the ratio of workers is proportional to the ratio of what these workers can produce. In the numerator is the death rate δ_t multiplied by the value of a life in utils, v_t: this is the total value of what can potentially be gained by making a lifesaving good. The denominator, in contrast, is proportional to what can be gained by making consumption goods: the level of consumption multiplied by the marginal utility of consumption to put it in utils, as in the numerator.

In the analysis of this equation, it turns out to be useful to define $\tilde{v}_t \equiv v_t/u'(c_t)c_t$: the value of a life in consumption units as a ratio to the level of consumption. This is the analogue to $u(c)/u'(c)c$ in the Russian roulette model, where lives last for one period; in fact, one can show—see equation (A4) in Appendix A—that the two are proportional here.

The allocation of workers then depends on the product $\delta_t\tilde{v}_t$. In fact, as shown in Appendix A, the allocation of scientists depends on exactly this same term; see equation (A3). Over time, the number of deaths that can potentially be avoided, δ_t, declines. However, the value of each life rises. When $\gamma > 1$, the value of life rises even as a ratio to consumption, so $\tilde{v}_t$ rises. Then it is a race: δ_t falls at a rate proportional to β, while $\tilde{v}_t$ rises at a rate proportional to $\gamma - 1$; hence the critical role of $\gamma - 1 - \beta$. In particular, when γ is large, as in the proposition just stated, the value of life rises very rapidly, so that $\delta_t\tilde{v}_t$ rises to infinity. In this case, the optimal allocation shifts all the labor and scientists into the life sector: the value of the lives that can be saved rises so fast that it is optimal to devote ever-increasing resources to saving lives.

E. *The Optimal Allocation with* $\gamma < 1 + \beta$

What happens if the marginal utility of consumption does not fall quite so rapidly? The intuition is already suggested by the analysis just provided, and the result is given explicitly in the next proposition.

Proposition 3 (Optimal growth with $\gamma < 1 + \beta$). Assume that the marginal utility of consumption falls, but not too rapidly, in the sense that $\gamma < 1 + \beta$. Then the optimal allocation features an asymptotic constant growth path such that as $t \to \infty$, the fraction of labor working in the life sector $\tilde{\ell}_t \equiv 1 - \ell_t$ and the fraction of scientists making lifesaving ideas $\tilde{s}_t \equiv 1 - s_t$ both fall to zero at constant exponential rates, and asymptotic growth is given by

$$g_A^* = \frac{\lambda \bar{n}}{1-\phi}, \quad g_B^* = \frac{\lambda(\bar{n} + g_{\tilde{s}}^*)}{1-\phi} < g_A^*,$$

$$g_c^* = \bar{g} \equiv \frac{\alpha\lambda\bar{n}}{1-\phi}, \quad g_\delta^* = -\beta g_h^*,$$

and the exact values for $g_{\tilde{s}}^*$ and g_h^* depend on whether $\gamma > 1$ or $\gamma \le 1$. In particular, if $1 < \gamma < 1 + \beta$,

$$g_{\tilde{s}}^* = g_{\tilde{\ell}}^* = \frac{-\bar{g}(\beta + 1 - \gamma)}{1 + \beta\left(1 + \frac{\alpha\lambda}{1-\phi}\right)} < 0, \tag{28}$$

$$g_h^* = \bar{g} \cdot \left[\frac{1 + (\gamma - 1)\left(1 + \frac{\alpha\lambda}{1-\phi}\right)}{1 + \beta\left(1 + \frac{\alpha\lambda}{1-\phi}\right)}\right] < \bar{g}. \tag{29}$$

While if $\gamma \le 1$,

$$g_{\tilde{s}}^* = g_{\tilde{\ell}}^* = \frac{-\beta\bar{g}}{1 + \beta\left(1 + \frac{\alpha\lambda}{1-\phi}\right)} < 0, \tag{30}$$

$$g_h^* = \bar{g} \cdot \left[\frac{1}{1 + \beta\left(1 + \frac{\alpha\lambda}{1-\phi}\right)}\right] < \bar{g}. \tag{31}$$

This proposition shows that when $\gamma < 1 + \beta$, the results flip-flop. That is, there is still a trend in the allocation of scientists and workers, but the trend is now away from the health/life sector and toward the consumption sector. In this case, the death rate falls faster than the value of life rises. Looking back at equation (27), the denominator $u'(c_t)c_t$ rises faster than the numerator: the greater gain is in providing consumption goods rather than in saving lives. We once again get an unbalanced growth result, but now it is the consumption sector that grows faster.

F. *"Interior" Growth When $\gamma = 1 + \beta$*

PROPOSITION 4 (Optimal growth with $\gamma = 1 + \beta$). Assume the following knife-edge condition relating preferences and technology: $\gamma = 1 + \beta$. Then the optimal allocation features an asymptotic balanced growth path such that as $t \to \infty$, the key allocation variables ℓ_t and s_t settle down to constants strictly between zero and one, and asymptotic growth is given by

$$g_A^* = g_B^* = \frac{\lambda \bar{n}}{1 - \phi},$$

$$g_c^* = g_h^* = \frac{\alpha \lambda \bar{n}}{1 - \phi} = \bar{g}, \quad g_\delta^* = -\beta \bar{g}.$$

This is the one case in which growth is "balanced" in the sense that the consumption and life sectors grow at the same rate and labor and scientists do not all end up in one sector. But, as stated above, this requires a somewhat arbitrary knife-edge condition relating technology and preferences. The intuition for this knife edge is that the model features two goods: consumption, whose marginal utility falls at rate $1 - \gamma$, and h, whose marginal utility falls at rate β. Unless these two rates are the same, the allocation will tilt in one direction or the other.

G. *Discussion*

Several points now merit discussion. First, the results suggest that growth in one sector is slower than what is feasible. What about overall GDP growth? To answer this question, one needs to construct a measure of GDP for this two-sector economy. Per capita GDP is $p_c c + p_h h$. We choose consumption as our numeraire ($p_c \equiv 1$). The relative price of h is then easy to obtain in this economy: given that one unit of labor can produce either A^α units of consumption or B^α units of the lifesaving good, the relative price of h is the marginal rate of transformation $(A/B)^\alpha$.

The growth rate of per capita GDP can then be calculated using the Divisia method, as a weighted average of the growth rates of c and h, where the weights are the nominal shares of c and h in GDP. Perhaps not surprisingly, it turns out that the share of consumption in GDP, $p_c c/(p_c c + p_h h)$, is equal to ℓ, the share of labor working in the consumption sector. Per capita GDP growth is then $\ell g_c + (1 - \ell)g_h$. But this means that GDP growth is asymptotically equal to $\bar{g}$ in all three cases above.[11] Our key result is about the composition of growth, and especially about the growth rate of consumption relative to what is feasible, rather than being a statement about overall GDP growth.

Next, notice another important point: the Russian roulette model at the start of the paper and the richer model developed subsequently lead to slightly different conclusions. In the Russian roulette model, consumption growth falls to zero when the marginal utility of consumption diminishes rapidly, while in the richer model consumption growth is only slowed by some proportion. Why the difference?

The answer turns on functional forms and modeling choices about which we have relatively little information. In the Russian roulette model, the mortality rate depends on the growth rate of the economy rather than on the level of technology, and this difference is evidently important. Preserving life there requires the growth rate to fall all the way to zero. One could enrich the Russian roulette model, for example, by embedding it in a Schumpeterian quality ladder model as in Aghion and Howitt (1992), where each idea increases consumption by a constant percentage while having a small risk of a disaster. One could even add a second lifesaving technology to this framework. Nevertheless, since the mortality rate and the growth rate of consumption would be linked, the logic just provided suggests that consumption growth would still optimally fall to zero in the case in which marginal utility declines rapidly.

In this sense, the Russian roulette model and the richer model of Section III are complements rather than substitutes. The general result is that concerns for safety can slow consumption growth, with the precise nature of the slowdown depending on modeling details.

IV. Empirical Evidence

The main model in this paper makes stark predictions regarding the composition of research. Depending on the relative magnitudes of $\gamma - 1$ and β, the direction of technical change should shift either toward or away from lifesaving technologies. In particular, if γ is large—so that the marginal utility of consumption declines rapidly—one would expect to see the composition of research shifting toward lifesaving technologies, thereby slowing consumption growth.

[11] Intuitively, workers and researchers are leaving the slow-growing sector; indeed, it is this fact that makes it slow growing. The sector they are attracted to does not suffer this depletion and grows at the expected semi-endogenous rate.

In this section, I discuss a range of evidence on β, γ, and the composition of research. While not entirely decisive, the bulk of the evidence is consistent with the first case considered, where there is an income effect for livesaving technologies and consumption growth is slowed.

Some general caveats should be noted before turning to the evidence. The analysis so far has considered an allocation chosen by a social planner. The evidence below, however, comes from real-world economies that feature a range of institutions, taxes, and imperfections. One can show that simple equilibrium allocations in our model (e.g., a Romer-style equilibrium with imperfect competition) would also display trends in allocations in the same cases, but this distinction is still worth noting. Second, the "lifesaving" sector in the model and the "health" sector in the data are not the same thing. The former includes goods such as fences around swimming pools and safer highways, while the latter includes cosmetic surgery and knee replacements. The overall point of the evidence below is not to test the model but rather to suggest that the case in which consumption growth is slowed may be empirically relevant.

A. *The Composition of Research*

One might think that the main prediction on the composition of research would be an easy prediction to test: surely there must be readily available statistics on research spending by the health sector of the economy. Unfortunately, this is not the case. The main reason appears to be that both the spending and performance of health research are done in several different organizations in the economy: industry, government, nonprofits, and academia. Thus, the construction of such numbers requires merging the results of different surveys, being careful to avoid double counting, considering changes in the surveys over time, and so on. Between the 1970s and the early 1990s, the National Institutes of Health (NIH) undertook this calculation and reported a health research number. But, unfortunately, I have not been able to find any other source that does this for the last 20 years.

Figure 2 shows the original NIH numbers for the United States, along with several attempts to extend this series to more recent years. Details are discussed in Appendix B.[12] In addition to the original NIH estimates, figure 2 shows three other series. The longest is noncommercial health research from the National Health Expenditure Accounts of the Centers for Medicare and Medicaid Services (CMMS). The remaining two series add estimates of commercial research to the CMMS estimate, using two different collections of surveys by the National Science Foundation (NSF). The fact that the NIH series and the CMMS+NSF series coincide during overlapping years is somewhat reassuring.

[12] I am grateful to Raymond Wolfe for guidance and suggestions with these data.

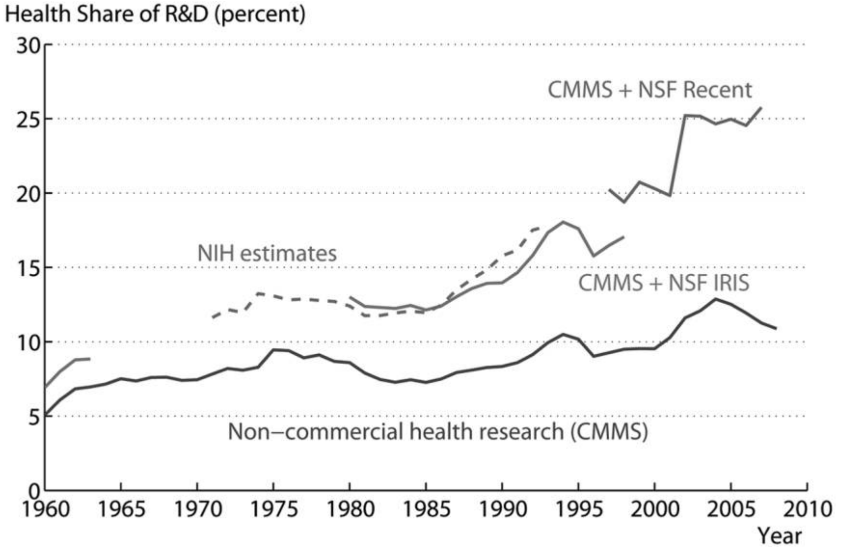

FIG. 2.—The changing composition of US R&D spending. The graph shows the rise in the share of R&D spending in the United States that is devoted to health, according to several different measures. See Appendix B for sources and methodology. Color version available as an online enhancement.

Figure 2 indicates that whether we look at noncommercial research or the broader estimates for total research, the composition of R&D appears to be shifting distinctly toward health over time. For example, the earliest estimates from 1960 suggest that the health sector accounted for only about 7 percent of all R&D, while the most recent estimates from 2007 are around 25 percent.

Lifesaving technologies are invented around the world, not just in the United States. Figure 3 uses OECD sources to study how the composition of R&D is changing internationally. These data are available only since 1991 but tell the same basic story: the composition of research is shifting distinctly toward health. In 1991, around 9 percent of OECD research spending was on health, and this share rose to 16 percent by 2006. The figure also shows the corresponding share for the United States (estimated using slightly different assumptions with these OECD sources), confirming the sharp rise that we saw earlier in figure 2.

Of course, there are other possible explanations for the changing composition of research. Perhaps the rise in the share of health spending in the economy is due to other factors (e.g., the insurance system favoring expensive technologies as in Weisbrod [1991]), and health research is simply responding to these factors as well.

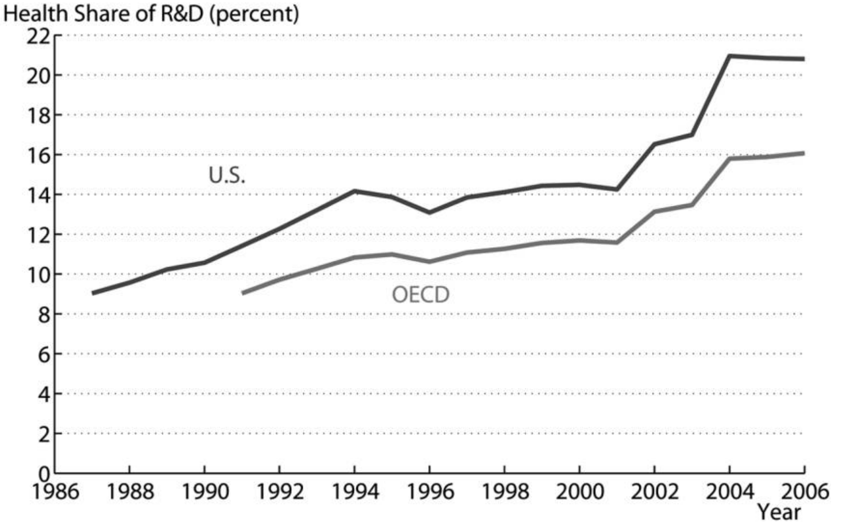

FIG. 3.—The changing composition of OECD R&D spending. The trend toward health is apparent in OECD measures of R&D expenditures as well. The OECD estimate reported here includes data from the United States, Canada, France, Germany, Italy, Japan, Spain, and the United Kingdom. See Appendix B for sources and methodology. Color version available as an online enhancement.

B. *Patents*

As an alternative to looking at the inputs to idea production, one can consider the output. Figure 4 shows the fraction of all patents granted by the US Patent Office between 1963 and 1999 for medical equipment and pharmaceuticals.[13] There are well-known limitations to using the patent data as a measure of idea production (e.g., the distribution of patent values is very skewed; see Griliches [1990] for a detailed discussion). However, as one of many pieces of evidence, patents are useful. The share of patents for medical equipment and pharmaceuticals rises from around 4 percent in 1963 to more than 13 percent in 1999. The dashed line in the figure shows one alternative cut of the data, restricting the universe to patents by US innovators. Similar strong upward trends can be found in other cuts of the data: just restricting to foreign innovators or for medical equipment and patents separately.

C. *Empirical Evidence on* β

The parameter β is readily interpreted as the elasticity of the mortality rate with respect to real lifesaving expenditures. A rough estimate for

[13] These data have been provided by Jeffrey Clemens and are discussed in detail in Clemens (2013).

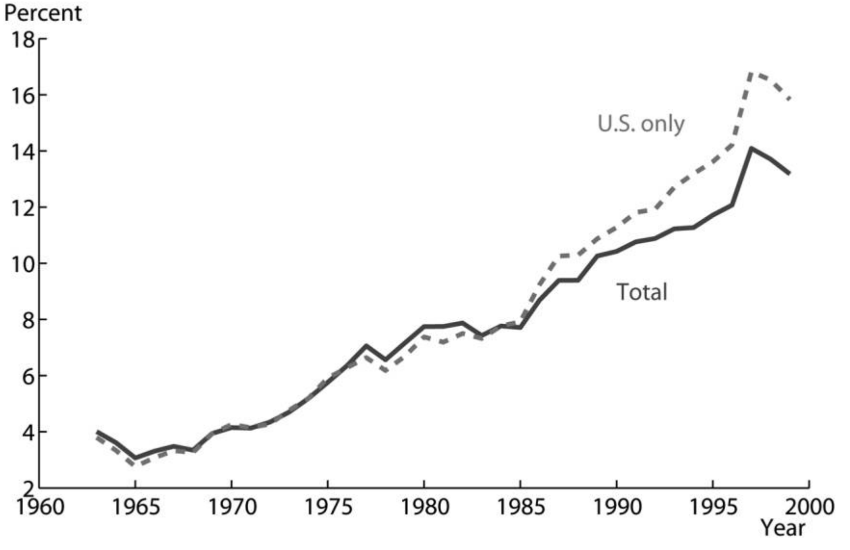

Fig. 4.—The fraction of patents for medical equipment or pharmaceuticals. "Total" refers to all patent grants in the NBER Patent Database. "US only" restricts the sample to patents granted to US innovators. See Clemens (2013). Color version available as an online enhancement.

this parameter can be obtained by considering the relative trends in mortality and health spending: this calculation attributes all the decline in mortality to health spending, which is probably an overestimate given the contribution of other factors such as education to declining mortality.

According to *Health, United States 2009*, age-adjusted mortality rates fell at an average annual rate of 1.2 percent between 1960 and 2007, while consumer price index (CPI) deflated health spending rose at an average annual rate of 4.1 percent.[14] The ratio of these two growth rates gives an estimate for β of 0.291. Hall and Jones (2007) conduct a more formal analysis along these lines using age-specific mortality rates and age-specific health spending and allowing for other factors to enter. For people between the ages of 20 and 80, they find estimates for this elasticity ranging from 0.10 to 0.25. These different estimates suggest that values of β substantially below one are plausible.

D. Estimates of γ

Given the estimates for β just reported, life considerations may dominate in the model if γ is larger than about 1.3. In the most common

[14] See tables 26 and 122 of that publication, available at http://www.cdc.gov/nchs/hus.htm.

way of specifying preferences for macro applications, the coefficient of relative risk aversion, γ in our notation, equals the inverse of the elasticity of intertemporal substitution. Large literatures on asset pricing (Lucas 1994) and labor supply (Chetty 2006) suggest that $\gamma > 1$ is a reasonable value, and values above 1.5 are quite common in this literature.

Evidence on the elasticity of intertemporal substitution, $1/\gamma$ in our notation, is more mixed. The traditional view, such as Hall (1988), is that this elasticity is well below one, consistent with the case of $\gamma > 1.3$. This view is supported by a range of careful microeconometric work, including Attanasio and Weber (1995), Barsky et al. (1997), and Guvenen (2006); see Hall (2009) for a survey of this evidence. On the other hand, Vissing-Jorgensen and Attanasio (2003) and Gruber (2006) find evidence that the elasticity of intertemporal substitution is greater than one, suggesting that $\gamma < 1$ could be appropriate.

Empirical evidence on the value of life.—Direct evidence on how the value of life changes with income—another way to gauge the magnitude of γ—is surprisingly difficult to come by. Most of the empirical work in this literature is cross-sectional in nature and focuses on getting a single measure of the value of life (or perhaps a value by age); see Ashenfelter and Greenstone (2004), for example. There are a few studies that contain important information on the income elasticity, however. Viscusi and Aldy (2003) conduct a meta-analysis and find that across studies, the value of life exhibits an income elasticity below one. On the other hand, Hammitt, Liu, and Liu (2000) and Costa and Kahn (2004) consider explicitly how the value of life changes over time. These studies find that the value of life rises roughly twice as fast as income, consistent with a value of γ around 2.

Evidence from health spending.—The key mechanism at work in this paper is that the marginal utility of consumption falls quickly if $\gamma > 1$, leading the value of life to rise faster than consumption. This tilts the allocation in the economy away from consumption growth and toward preserving lives. Exactly this same mechanism is at work in Hall and Jones (2007), which studies health spending. In that paper, $\gamma > 1$ leads to an income effect: as the economy gets richer over time (exogenously), it is optimal to spend an increasing fraction of income on health care in an effort to reduce mortality. The same force is at work here in a very different context. Economic growth combines with sharply diminishing marginal utility to make the preservation of life a luxury good. The novel finding is that this force has first-order effects on the determination of economic growth itself.

Figure 5 shows international evidence on health spending as a share of GDP. This share is rising in many countries of the world, not only in the United States. Indeed, for the 16 OECD countries reporting data

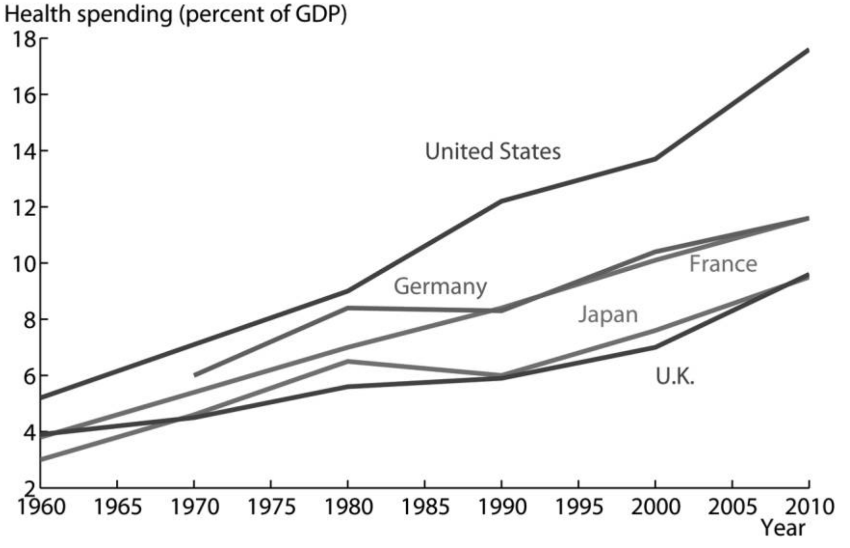

FIG. 5.—International evidence on the income effect in health spending. Data are from *OECD Health Data 2012* and are reported every 10 years. Color version available as an online enhancement.

in both 1971 and 2010 (many not shown), all experienced a rising health share.[15]

E. *Growth in Health and Nonhealth Consumption*

The results from our model suggest that, apart from a knife-edge case, the composition of research will shift toward either the consumption sector or the lifesaving sector. Moreover, at least insofar as the parameters of the idea production function are similar in those two sectors (and we have no real evidence pushing us one way or the other on this), the sector that sheds its researchers will grow more slowly in the long run.

This prediction prompts us to look at the historical evidence on the growth of per capita consumption for both the health and nonhealth

[15] Acemoglu, Finkelstein, and Notowidigdo (2009) estimate an elasticity of hospital spending with respect to transitory income of 0.7, less than one, using oil price movements to instrument local income changes at the county level in the southern part of the United States. (The instrument helps control for reverse causality, where poor health may cause lower incomes or where a third factor moves both health and income.) While useful, it is not entirely clear that this bears on the key parameter here, as that paper considers income changes that are temporary (and hence might reasonably be smoothed and not have a large effect on health spending) and local (and hence might not alter the limited selection of health insurance contracts that are available).

sectors, respectively. Figure 6 shows this evidence, taken from the National Income and Product Accounts (NIPA) for the United States.

The figure shows two lines for each sector, differing according to which price deflators are used. The "official" lines report the results using the official Bureau of Economic Analysis (BEA) deflators for health and nonhealth consumption. These results already suggest faster growth in health than in consumption, consistent with the evidence on the composition of research.

There is ample evidence, however, that serious measurement problems associated with quality change plague the construction of these deflators. Triplett and Bosworth (2000), for example, show that they imply negative labor productivity growth in the health sector, a finding that rings hollow given the rapid technological advances in that sector. Many case studies of particular health treatments find that quality-adjusted prices are actually falling rather than rising relative to the CPI.[16] The personal consumption expenditure (pce) measures in figure 6 therefore deflate both nominal health spending and nominal consumption spending by the overall NIPA deflator for pce, implicitly assuming that rates of technological change are the same in the two sectors. Of course, given the changing composition of research, even this correction arguably falls short. Nevertheless, one can see that it suggests a large difference in growth between the two sectors, with growth in health averaging 4.67 percent per year between 1950 and 2009 versus only 1.84 percent for per capita consumption.

If the economy were already in a steady state, the growth rates reported in figure 6 would be direct evidence on the magnitude of the "growth drag"—the extent to which consumption growth is reduced by life considerations relative to what is feasible. This estimate is substantial: $1.84/4.67 \approx 0.4$, for example, suggesting that consumption growth is reduced to only 40 percent of its feasible rate because of the rising importance of life.

However, the evidence on the composition of research suggests that the economy is far from its steady state, since the research share in health is well below one. This evidence on the growth drag, then, is only sugges-

[16] Cutler et al. (1998) find that the real quality-adjusted price for treating heart attacks declines at a rate of 1.1 percent per year between 1983 and 1994. Shapiro, Shapiro, and Wilcox (1999) examine the treatment price for cataracts between 1969 and 1994. While a CPI-like price index for cataracts increased at an annual rate of 9.2 percent over this period, their alternative price index, only partially incorporating quality improvements, grew only 4.1 percent per year, falling relative to the total CPI at a rate of about 1.5 percent per year. Berndt et al. (2000) estimate that the price of treating incidents of acute phase major depression declined in nominal terms by between 1.7 percent and 2.1 percent per year between 1991 and 1996, corresponding to a real rate of decline of more than 3 percent (though over a relatively short time period). Lawver (2011) obtains similar results using a structural model and more aggregate data.

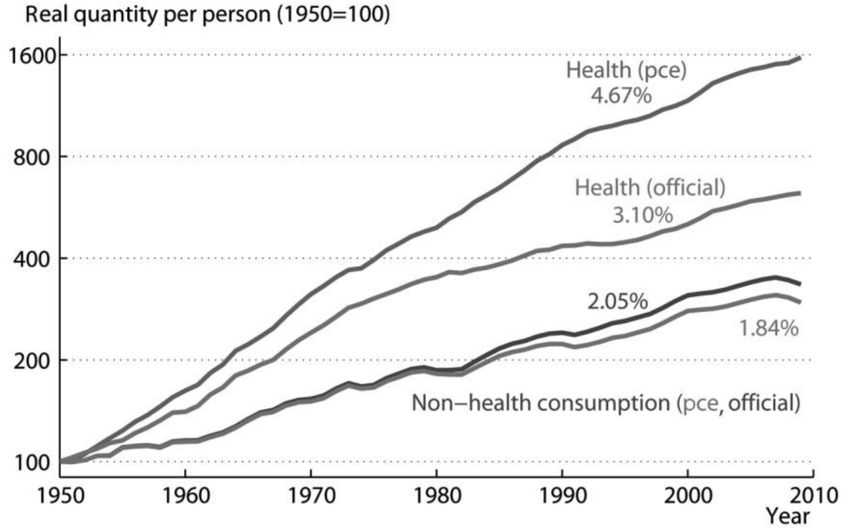

FIG. 6.—Health and consumption. The plot shows real per capita consumption expenditures for health and nonhealth in the United States. Two different methods are used to deflate nominal expenditures. The "official" lines are deflated by the price indices constructed by the BEA, which show more rapid price increases in the health sector. The "pce" lines are both deflated by the overall deflator for personal consumption expenditures, implicitly assuming that technical change in the two sectors occurs at the same rate (a conservative assumption given the general empirical evidence reported in this paper). Color version available as an online enhancement.

tive. As the next section shows, one can calibrate the model to get an estimate of the growth drag that is in the same ballpark as this historical evidence.

V. Calibration and Quantitative Results

A. Calibrating the Growth Drag

The previous section discussed a range of evidence: the shift in the composition of research and patenting toward health, empirical estimates of β and γ, how the value of life changes with income, the rise in health spending as a share of GDP, and the historical evidence on the growth rates of health spending versus nonhealth consumption. While none is entirely decisive, the evidence suggests that the possibility of an income effect favoring lifesaving technologies should be considered carefully. The case studied in proposition 2 in which $\gamma > 1 + \beta$ may be the relevant one.

Here, I follow this logic and, using a range of parameter values consistent with the evidence just discussed, report the magnitude of the consumption "growth drag" that is implied. More precisely, recall that according to proposition 2, long-run growth rates in the two sectors are given by

$$g_h^* = \frac{\alpha\lambda\bar{n}}{1-\phi} = \bar{g}, \tag{32}$$

$$g_c^* = \bar{g} \cdot \frac{1 + \beta\left(1 + \frac{\alpha\lambda}{1-\phi}\right)}{1 + (\gamma - 1)\left(1 + \frac{\alpha\lambda}{1-\phi}\right)} < \bar{g}. \tag{33}$$

That is, when $\gamma - 1 > \beta$, the consumption sector grows more slowly than the health sector—and more slowly than what is feasible—by a factor that is given in the last equation.

To estimate this factor, we require estimates of γ, β, and $\alpha\lambda/(1-\phi)$. I have already discussed evidence on the first two of these above. Notice from equation (32) that the last is just given by the factor by which the long-run growth rate of the health sector is "marked up" over the rate of population growth. Estimates of this factor for the economy as a whole are discussed in Jones and Romer (2010); a broad but plausible range for this factor is [1/2, 2]; larger values would simply make the growth drag even more dramatic.

Table 1 reports estimates of the "growth drag" factor in equation (33). These factors range from a low of 0.33 to a high of 0.79, with the mean value equal to 0.56. That is, according to the mean value, long-run growth in the consumption sector is only 56 percent of its feasible rate in the optimal allocation. It would be feasible to keep the research shares

TABLE 1
The Consumption Growth Drag

	$\beta = .25$		$\beta = .10$	
$\alpha\lambda/(1-\phi)$	$\gamma = 1.5$	$\gamma = 2$	$\gamma = 1.5$	$\gamma = 2$
.50	.79	.55	.66	.46
1.00	.75	.50	.60	.40
2.00	.70	.44	.52	.33

Note.—The table reports the ratio of g_c to g_h in the steady state according to proposition 2 for various values of the parameters. That is, it reports the factor by which consumption growth gets reduced because of the trend in the research share. The factor is

$$\frac{1 + \beta\left(1 + \frac{\alpha\lambda}{1-\phi}\right)}{1 + (\gamma - 1)\left(1 + \frac{\alpha\lambda}{1-\phi}\right)}.$$

The mean across the various estimates is 0.56.

constant and let consumption grow much faster, but the rising value of life means this is not optimal.[17]

This growth drag calculation illustrates a deeper conceptual point about the model. The standard interpretation of semi-endogenous growth models (like this one) is that conventional policies cannot affect the long-run growth rate. However, that is incorrect in this case. Policies that alter the rate at which the consumption sector sheds researchers can change the magnitude of the growth drag and hence affect the long-run growth rate of consumption.

B. *Numerical Results for Transition Dynamics*

The analysis so far suggests that consumption growth in the long-run may be substantially less than what is feasible. However, this is an asymptotic result. To see the relevance of the analysis to an economy away from the steady state, I solve the model numerically.

I choose parameter values, including β and γ, to target several stylized facts for the US economy. In particular, I seek to find a year t_0 in which the value of a year of life as a ratio to per capita consumption is 3.5 (e.g., a value of a life year of \$125,000 and per capita consumption of \$36,000), in which per capita GDP growth is 2 percent, and in which 25 percent of research scientists work in the life sector. This leads to $\beta = 0.6006$ and $\gamma = 2.6953$; details of the solution method and other parameter values are given in Appendix C.

This exercise should not be viewed as a formal calibration designed to replicate the US data. First, the model is based on the optimal allocation, but there are ample reasons to doubt that the US allocation—with various institutions such as Medicare and the NIH, with market failures in the health system—is optimal. Second, there are too many parameters of the model, such as the parameters of the two idea production functions, that we do not have good information about. Finally, the mapping between the data and the model is imprecise. What counts as research according to the NSF is much narrower than what an economist would count as research, and the health sector in the data is only a rough match to the life sector in the model. Instead, it is best to view the numerical exercise as an illustration of the basic transition dynamics that are possible in this framework.

[17] Stokey (1998) and Brock and Taylor (2005) document a related "growth drag" associated with environmental considerations. In these papers, pollution enters the utility function as a cost in an additively separable fashion from consumption. These models feature an income effect for $\gamma > 1$ because the utility from growing consumption is bounded. This leads to a growth drag from the environment: consumption growth is slower than it would otherwise be because of environmental concerns.

Figure 7 show the key allocation variables, and figure 8 shows various growth rates along the transition path. In these figures, the date $t_0 = 66$ corresponds to the US economy today, and a period represents a year.

Consider first the allocation variables shown in figure 7. The fraction of research scientists working in the consumption sector, s, starts extremely close to 100 percent, as does the fraction of workers in the consumption sector, ℓ. Recall that this latter variable also equals the consumption share of GDP. Both s and ℓ decline steadily in this calibration, asymptoting to zero. In the year $t_0 = 66$, we have $s = .79$ and $\ell = .64$, corresponding to a 21 percent share of researchers in the life sector and an optimal "life" share of GDP of 36 percent.

The other allocation shown in the figure is σ, the fraction of the population optimally engaged in research. From an initial value of around 10 percent, this fraction rises to its steady-state value of 28 percent.

Figure 8 shows various growth rates along the transition path, including the growth rate of per capita GDP. Several key features of the growth figure stand out. First, the growth rate of per capita GDP in year t_0 is 1.9 percent per year. This rate is in turn an average of a consumption growth rate of 1.6 percent and a life sector growth rate of 2.2 percent.

While the growth rate of h substantially exceeds the growth rate of c in the early years of the simulation, it is interesting to notice that the

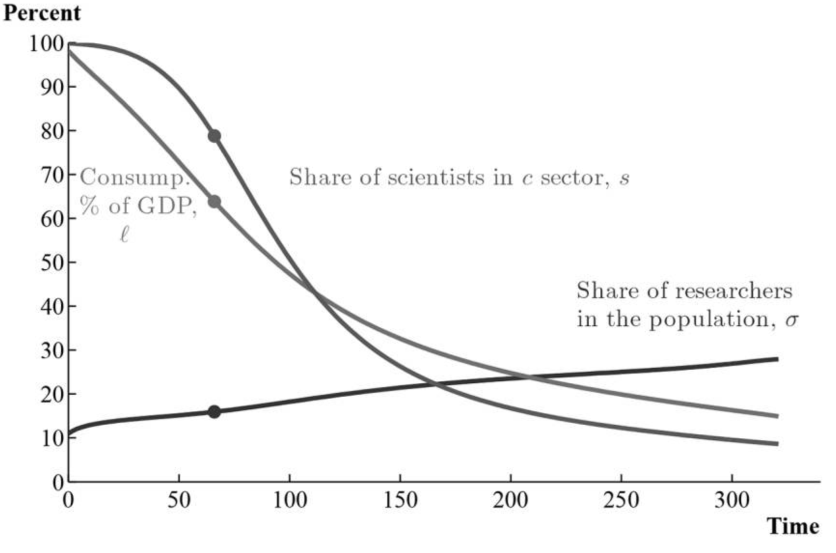

FIG. 7.—The allocation along the transition path. Time $t_0 = 66$ corresponds to "today," and values at this date are highlighted by filled circles. Key parameter values are $\gamma = 2.6953$, $\beta = 0.6006$, $\bar{u} = .001$, $\lambda = .5377$, $\delta_T = .0002$, and $\phi = 5/6$. See Appendix C for the details of the numerical solution. Color version available as an online enhancement.

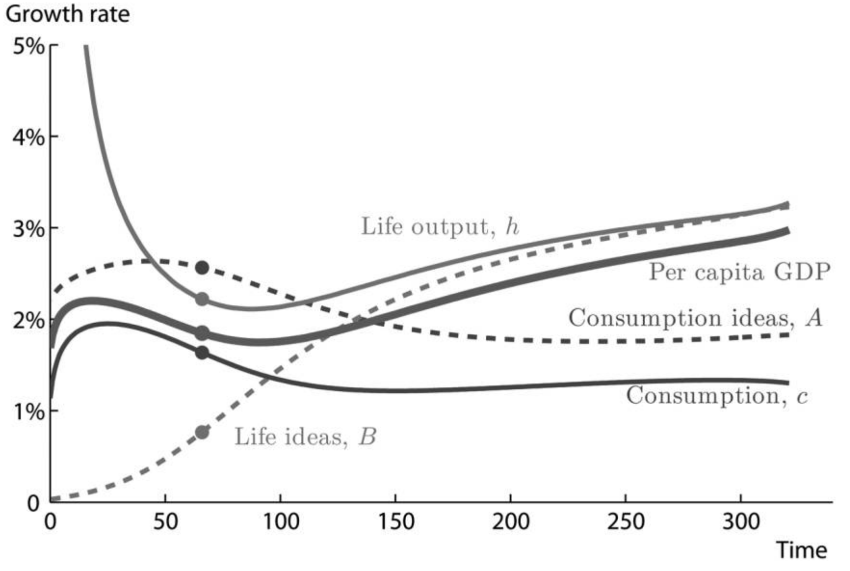

FIG. 8.—Growth rates along the transition path (see fig. 7). Color version available as an online enhancement.

reverse is true for the rates of technological change. That is, g_{At} is much faster than g_{Bt} initially. The life sector grows rapidly at first because more and more people are shifting to work in that sector, not because of faster technological change. The relative price of h is therefore actually rising for the first 130 years of the numerical example, much as it is in the official US data.

Turning now to the long run, notice that the long-run feasible growth rate of both sectors is $\bar{g} = 3.2$ percent. The life sector achieves this growth rate in the long run, as does per capita GDP since the life share goes to one. In contrast, the long-run growth rate of the consumption sector is just 1.3 percent. So this numerical example features a rising growth rate of per capita GDP as the economy shifts toward the life sector but a declining growth rate of (nonhealth) consumption per person.

As discussed in Appendix C, other qualitatively different transition dynamics are possible in this model, depending on parameter choices. What this numerical example shows is one possibility in which the parameter values are chosen to target a few key moments in the data.

VI. Conclusion

Technological progress involves life and death, and augmenting standard growth models to take this into account leads potentially to first-order changes in the theory of economic growth. This paper explores these possibilities, first in a simple "Russian roulette" style model in which new ideas can rarely cause disasters and then in a richer model that features two kinds of ideas, those that increase consumption and those that save lives. The results depend somewhat on the details of the model and, crucially, on how rapidly the marginal utility of consumption declines. It may be optimal for consumption growth to continue exponentially despite the presence of life-and-death considerations. Or it may be optimal for consumption growth to slow substantially relative to what is feasible, even potentially leading to a steady-state level of consumption.

The intuition for these results turns out to be straightforward. For a large class of standard preferences, safety is a luxury good. The marginal utility associated with more consumption on a given day runs into sharp diminishing returns, and ensuring additional days of life on which to consume is a natural, welfare-enhancing response. When the value of life rises faster than consumption, economic growth leads to a disproportionate concern for safety. This concern can be so strong that it is desirable that consumption growth be restrained.

This paper suggests a number of different directions for future research on the economics of safety. It would clearly be desirable to have precise estimates of the value of life and how this has changed over time; in particular, does it indeed rise faster than consumption? More empirical work on how safety standards have changed over time—and estimates of their impacts on economic growth—would also be valuable. Finally, the basic mechanism at work in this paper over time also applies across countries. Countries at different levels of income may have very different values of life and therefore different safety standards. This may have interesting implications for international trade, standards for pollution and global warming, and international relations more generally.

Appendix A

Derivations and Proofs

This appendix contains outlines of the proofs of the propositions reported in the paper. As a prelude to these propositions, I first consider the optimal allocation problem in equations (16)–(21). Using the Hamiltonian in (22) and applying the maximum principle, the first-order necessary conditions for a solution are

$$\frac{1-s_t}{s_t} = \frac{p_{bt}\dot{B}_t}{p_{at}\dot{A}_t}, \qquad \text{(FOC: } s\text{)}$$

$$\frac{1-\ell_t}{\ell_t} = \beta\delta_t \cdot \frac{v_t}{u'(c_t)c_t}, \qquad \text{(FOC: } \ell\text{)}$$

$$\frac{\sigma_t}{1-\sigma_t} = \frac{\lambda(p_{at}\dot{A}_t + p_{bt}\dot{B}_t)}{M_t[u'(c_t)c_t + \beta\delta_t v_t]}, \tag{FOC: σ}$$

$$\rho = \frac{\dot{v}_t}{v_t} + \frac{1}{v_t}[u(c_t) - v_t\delta_t], \tag{FOC: M}$$

$$\rho = \frac{\dot{p}_{at}}{p_{at}} + \frac{1}{p_{at}}\left[M_t u'(c_t)\alpha\frac{c_t}{A_t} + p_{at}\phi\frac{\dot{A}_t}{A_t}\right], \tag{FOC: A}$$

$$\rho = \frac{\dot{p}_{bt}}{p_{bt}} + \frac{1}{p_{bt}}\left(p_{bt}\phi\frac{\dot{B}_t}{B_t} + \alpha\beta v_t M_t\frac{\delta_t}{B_t}\right), \tag{FOC: B}$$

plus the three standard transversality conditions.

It will be convenient, for reasons discussed in the main text, to define

$$\tilde{v}_t \equiv \frac{v_t}{u'(c_t)c_t}.$$

This variable denotes the ratio of the value of life to consumption per person.

Proof of Proposition 2: Optimal Growth with $\gamma > 1 + \beta$

The essence of the result is that the key allocation variables s_t and ℓ_t decline exponentially to zero at a constant rate. This exponential shift of scientists toward the life sector slows the growth rate of consumption ideas. To derive the result, I use the various first-order conditions for the optimal allocation.

1. Look back at the first-order condition characterizing the allocation of scientists, equation (FOC: s). To solve for this allocation, we need to solve for the relative price of ideas, p_b/p_a. From equations (FOC: A) and (FOC: B), we have

$$p_{at} = \frac{\alpha M_t u'(c_t)c_t/A_t}{\rho - g_{p_a t} - \phi g_{At}} \quad \text{and} \quad p_{bt} = \frac{\alpha\beta M_t v_t\delta_t/B_t}{\rho - g_{p_b t} - \phi g_{Bt}}. \tag{A1}$$

A condition on the parameter values (basically that ρ is sufficiently large) keeps the denominators of these expressions positive. This means that the relative price satisfies

$$\frac{p_{bt}B_t}{p_{at}A_t} = \beta\delta_t\tilde{v}_t \cdot \frac{\rho - g_{p_a t} - \phi g_{At}}{\rho - g_{p_b t} - \phi g_{Bt}}. \tag{A2}$$

2. Substituting this expression into (FOC: s) yields

$$\frac{1-s_t}{s_t}=\beta\delta_t\tilde{v}_t\cdot\frac{\rho-g_{p_a t}-\phi g_{At}}{\rho-g_{p_b t}-\phi g_{Bt}}\cdot\frac{g_{Bt}}{g_{At}}. \tag{A3}$$

Recall from (FOC: ℓ) that $(1-\ell_t)/\ell_t=\beta\delta_t\tilde{v}_t$, so both of these key allocation variables depend on $\delta_t\tilde{v}_t$, that is, on the race between the decline in the mortality rate and the possible rise in the value of life relative to consumption. The next several steps characterize the behavior of $\delta_t\tilde{v}_t$, which we will then plug back into this expression.

3. First, consider $\tilde{v}_t$. Using (FOC: M), we obtain

$$\tilde{v}_t=\frac{u(c_t)/u'(c_t)c_t}{\rho+\delta_t-g_{vt}}. \tag{A4}$$

This is a key expression: the value of life in the economy (as a ratio to consumption) depends crucially on the extra utility that person enjoys. The denominator essentially converts this flow dividend into a present discounted value.

4. Now recall that given our constant relative risk aversion form for flow utility,

$$\frac{u(c_t)}{u'(c_t)c_t}=\bar{u}c_t^{\gamma-1}+\frac{1}{1-\gamma}.$$

Since $\gamma>1$, along an asymptotic BGP in which $c_t\to\infty$,

$$g_{\tilde{v}}=(\gamma-1)g_c \tag{A5}$$

as long as δ_t converges to some constant.

5. Now let us guess that the solution for the asymptotic BGP takes the following form: s_t and ℓ_t fall toward zero at a constant exponential rate, while $\sigma_t\to\sigma^*$. We will see that the key condition delivering this result will be $\gamma>1+\beta$.

6. Under this proposed solution, consumption growth is

$$g_c=\alpha g_A+g_\ell=\alpha g_A+g_s, \tag{A6}$$

where the last equality comes from observing that along our proposed asymptotic BGP, $g_\ell=g_s$ since both s_t and ℓ_t are inversely proportional to $\delta_t\tilde{v}_t$; see (A3) above.

7. A number of other growth rates follow in a straightforward way from the various production functions. Most important of these is the growth rate of A_t. Recall $\dot{A}_t=s_t^\lambda\sigma_t^\lambda N_t^\lambda A_t^\phi$ and $\dot{B}_t=(1-s_t)^\lambda\sigma_t^\lambda N_t^\lambda B_t^\phi$. The exponential decline in s_t will then crucially distinguish the growth rates of A_t and B_t, since $1-s_t\to 1$ will be asymptotically constant, while s_t falls exponentially. Therefore, taking logs and derivatives of these equations, their asymptotic growth rates must satisfy

$$g_A=\frac{\lambda(\bar{n}+g_s)}{1-\phi}\quad\text{and}\quad g_B=\frac{\lambda\bar{n}}{1-\phi}. \tag{A7}$$

8. Combining (A5), (A6), and (A7) gives

$$g_{\tilde{v}} = (\gamma - 1)\left[\frac{\alpha\lambda(\bar{n} + g_s)}{1 - \phi} + g_s\right]. \tag{A8}$$

9. So to get the growth rate of $\delta_t \tilde{v}_t$, we now need an expression for g_δ. Recall $\delta_t = [B_t^\alpha(1 - \ell_t)(1 - \sigma_t)]^{-\beta}$. Since $1 - \ell_t$ converges to one while $\sigma_t \to \sigma^*$,

$$g_\delta = -\alpha\beta g_B. \tag{A9}$$

10. Now, finally, look back at (A3) and consider the asymptotic growth rate of each side of the equation. Along our proposed BGP, $1 - s_t$ converges to one, so its growth rate converges to zero. The share s_t falls exponentially, leading the left side to grow, while the right side of the equation grows as $\delta_t \tilde{v}_t$. Using the last two results in (A8) and (A9), taking growth rates of (A3) gives

$$-g_s = -\alpha\beta g_B + (\gamma - 1)\left[\frac{\alpha\lambda(\bar{n} + g_s)}{1 - \phi} + g_s\right]. \tag{A10}$$

Solving for g_s then gives

$$g_s = \frac{-\alpha g_B(\gamma - 1 - \beta)}{1 + (\gamma - 1)\left(1 + \dfrac{\alpha\lambda}{1 - \phi}\right)}. \tag{A11}$$

Under the key assumption that $\gamma > 1 + \beta$, this solution for g_s is negative, as I conjectured earlier.

11. For completeness, one can also solve for σ^*, the share of the population that becomes scientists. Using (FOC: σ) and making some natural substitutions, we find

$$\frac{\sigma^*}{1 - \sigma^*} = \frac{\alpha\lambda g_B}{\rho - g_{p_b} - \phi g_B},$$

where, from (A1), $g_{p_b} = -(1 + \alpha\beta)g_B$. This means that

$$\frac{\sigma^*}{1 - \sigma^*} = \frac{\alpha\lambda g_B}{\rho + (1 - \phi + \alpha\beta)g_B}. \tag{A12}$$

Proof of Proposition 3: Optimal Growth with $\gamma < 1 + \beta$

The first part of the proof follows exactly what we did earlier in proving proposition 2. In particular, steps 1–3 are identical.

4. Here things start to change, depending on whether $\gamma \le 1$ or $1 < \gamma < 1 + \beta$. Notice that

$$\frac{u(c_t)}{u'(c_t)c_t} = \bar{u}c_t^{\gamma-1} + \frac{1}{1 - \gamma}.$$

If $\gamma \le 1$, this ratio (the value of a year of life relative to consumption) will converge to a constant as $c_t \to \infty$, whereas if $\gamma > 1$, the ratio will grow to infinity. This turns out not to matter very much in what follows. In particular, I will focus on the $\gamma > 1$ case below, so that

$$g_{\tilde{v}} = (\gamma - 1)g_c. \tag{A13}$$

(To consider the case in which $\gamma < 1$, simply replace the $\gamma - 1$ terms below with a zero, reflecting the appropriate value of $g_{\tilde{v}}$.)

5. Now we can guess that the solution for the asymptotic BGP takes the following form: $\tilde{s}_t \equiv 1 - s_t$ and $\tilde{\ell}_t \equiv 1 - \ell_t$ fall toward zero at a constant exponential rate, while $\sigma_t \to \sigma^*$. That is, the allocation of scientists and workers shifts away from life and toward the consumption sector.

6. Under this proposed solution, consumption growth is

$$g_c = \alpha g_A \tag{A14}$$

while growth of the lifesaving aggregate is

$$g_h = \alpha g_B + g_{\tilde{\ell}} = \alpha g_B + g_{\tilde{s}}. \tag{A15}$$

The last inequality comes from noting that $g_{\tilde{\ell}} = g_{\tilde{s}}$ from step 2 in the proof of proposition 2; see the discussion surrounding equation (A3) above. In fact, it is helpful to repeat that equation here, written in terms of the tilde variables:

$$\frac{\tilde{s}_t}{1 - \tilde{s}_t} = \beta\delta_t\tilde{v}_t \cdot \frac{\rho - g_{p_a t} - \phi g_{At}}{\rho - g_{p_b t} - \phi g_{Bt}} \cdot \frac{g_{Bt}}{g_{At}}. \tag{A16}$$

7. A number of other growth rates follow in a straightforward way from the various production functions. Most important of these is the growth rate of B_t. Recall $\dot{A}_t = (1 - \tilde{s}_t)^\lambda \sigma_t^\lambda N_t^\lambda A_t^\phi$ and $\dot{B}_t = \tilde{s}_t^\lambda \sigma_t^\lambda N_t^\lambda B_t^\phi$. The exponential decline in $\tilde{s}_t$ will then crucially distinguish the growth rates of A_t and B_t, since $1 - \tilde{s}_t \to 1$ will be asymptotically constant, while $\tilde{s}_t$ falls exponentially. Therefore, taking logs and derivatives of these equations, their asymptotic growth rates must satisfy

$$g_A = \frac{\lambda\bar{n}}{1 - \phi} \quad \text{and} \quad g_B = \frac{\lambda(\bar{n} + g_{\tilde{s}})}{1 - \phi}. \tag{A17}$$

8. Combining (A13), (A14), and (A17) gives

$$g_{\tilde{v}} = (\gamma - 1)\bar{g}. \tag{A18}$$

9. So to get the growth rate of $\delta_t\tilde{v}_t$, we now need an expression for g_δ. Recall $\delta_t = [B_t^\alpha \tilde{\ell}_t(1 - \sigma_t)]^{-\beta}$. Therefore, $g_\delta = -\beta(\alpha g_B + g_{\tilde{\ell}})$. Using this and the fact that $g_{\tilde{\ell}} = g_{\tilde{s}}$ gives

$$g_\delta = -\beta\left[\frac{\alpha\lambda(\bar{n} + g_{\tilde{s}})}{1 - \phi} + g_{\tilde{s}}\right]. \tag{A19}$$

Combining (A18) and (A19) leads to

$$g_\delta + g_{\tilde{v}} = -(1 + \beta - \gamma)\bar{g} - \beta g_{\tilde{s}}\left(1 + \frac{\alpha\lambda}{1 - \phi}\right). \tag{A20}$$

10. Now, look back at (A16) and consider the asymptotic growth rate of each side of the equation. Along our proposed BGP, $1 - \tilde{s}_t$ converges to one, so its

growth rate converges to zero. The share $\tilde{s}_t$ falls exponentially, while the right side of the equation grows with $\delta_t \tilde{v}_t$. Using our last several results in (A18), (A19), and (A20) gives

$$g_{\tilde{s}} = -(\beta + 1 - \gamma)\bar{g} - \beta g_{\tilde{s}}\left(1 + \frac{\alpha\lambda}{1-\phi}\right). \tag{A21}$$

Solving for $g_{\tilde{s}}$ then gives

$$g_{\tilde{s}} = \frac{-\bar{g}(\beta + 1 - \gamma)}{1 + \beta\left(1 + \frac{\alpha\lambda}{1-\phi}\right)}. \tag{A22}$$

Under our key assumption that $\gamma < 1 + \beta$, this solution for $g_{\tilde{s}}$ is negative, as we conjectured earlier.

11. Substituting this result into (A15) then gives the growth rate of the lifesaving aggregate:

$$g_h^* = \bar{g} \cdot \left[\frac{1 + (\gamma - 1)\left(1 + \frac{\alpha\lambda}{1-\phi}\right)}{1 + \beta\left(1 + \frac{\alpha\lambda}{1-\phi}\right)}\right] < \bar{g}. \tag{A23}$$

Proof of Proposition 4: Optimal Growth with $\gamma = 1 + \beta$

The proof here is straightforward and follows from the earlier proofs. For example, since $\gamma = 1 + \beta$, one can see from equation (A11) that $g_s = 0$. The key growth rates of the economy are then equal to $\bar{g}$ immediately.

Appendix B

Data

This appendix describes the construction of the data on the fraction of R&D expenditures associated with health. Two separate efforts are made, one using US data and the other using OECD data. These are discussed in turn.

A. United States

Several main sources are used to construct the US data underlying figure 2. A spreadsheet available from the data section of my webpage, http://www.stanford.edu/~chadj/NSF-AllYears-IndustrialRND.xls, contains the detailed calculations.

First, for the years 1971–93, various issues of the *NIH Data Book* report a time series for the key variable in which we are interested: the fraction of R&D related to health. In particular, I use the *NIH Data Books* for 1982, 1989, and 1994, splicing together these series during overlapping years to construct the first measure of health R&D. Unfortunately, these data do not appear to be available online, so I used physical copies of the data books.

The other measures are obtained from a more involved calculation using the following sources:

- Centers for Medicare and Medicaid Services, National Health Expenditure Accounts, 1960–2009 (https://www.cms.gov/nationalhealthexpenddata/02_nationalhealthaccountshistorical.asp). This data source provides an extensive account of health expenditures, including a "research" category. However, because the purpose is to provide an accounting of health expenditures, the research category includes only noncommercial research. As stated on page 26 of *National Health Expenditure Accounts: Definitions, Sources, and Methods 2009*, "Research shown separately in the NHEA is that of nonprofit or government entities. Research and development expenditures by drug and medical supply and equipment manufacturers are not shown in this line, as those expenditures are treated as intermediate purchases under the definitions of national income accounting; that is, the value of that research is deemed to be recouped through product sales."
- National Science Foundation Industrial Research and Development Information System data, 1953–98, table H-25 (http://www.nsf.gov/statistics/iris/excel-files/historical_tables/h-25.xls). From this source, I obtain "Company and Other (Except Federal) Funds for Industrial R&D Performance, by Industry" for 1953–98. In particular, I sum three industries to get commercial health research: "drugs and medicines" (Standard Industrial Classification [SIC] 283), "health services" (SIC 80), and then a fraction of "optical, surgical, photographic, and other instruments" (SIC 384–387). This fraction is equal to 0.569, which is obtained by using the average ratio of health R&D on "medical equipment and supplies" for 1997 and 1998 (the two overlapping years) from the next source.
- National Science Foundation, Research and Development in Industry (http://www.nsf.gov/statistics/industry/), various issues (2000, 2002, 2003, 2004, 2005). This source reports "Company and Other Nonfederal Funds for Industrial R&D Performance" for various years using the North American Industry Classification System. I sum three industries to get commercial health research: pharmaceuticals and medicines (3254), medical equipment and supplies (3391), and health care services (621–623). Raymond Wolfe kindly provided the 2006 and 2007 versions of these data.
- Finally, total spending on R&D is obtained from the National Science Foundation, National Patterns of R&D Resources: 2008 Data Update (http://www.nsf.gov/statistics/natlpatterns/, which reports data for 1953–2008.

Notice that the measures of commercial/industry R&D exclude federal funds but do include nonprofit or state and local funding for R&D. This may result in some double counting. The comparison of the *NIH Data Book* numbers to those that I construct from the NSF sources suggests that this is not a large problem; see figure 2 in the paper.

B. OECD

The OECD (and US) data underlying figure 3 are taken from the OECD iLibrary. A spreadsheet available from the data section of my webpage, STAN-Health-

RND.xls (http://www.stanford.edu/~chadj/STAN-HealthRND.xls), contains the detailed calculations.

Two sets of data from the OECD iLibrary are used:

- Government budget appropriations or outlays for R&D (http://dx.doi.org/10.1787/strd-data-en): This source provides government spending on R&D for health and overall from 1981 to 2007 in current purchasing power parity adjusted US dollars.
- STAN R&D Expenditure in Industry (ISIC Rev. 3) ANBERD ed2009 (http://stats.oecd.org/Index.aspx?DataSetCode=ANBERD_REV3): This source provides spending on R&D by industry. Because of a relatively limited industry breakdown, the health measure is the sum of spending in the pharmaceutical industry (C2423) and 0.5 times the spending in the "medical, precision, and optical instruments" industry (C33); this weight of 0.5 is obviously arbitrary but was suggested by calculations using the US sources discussed earlier.

From these data, I calculate the health share of R&D for both the United States and a set of OECD countries. For government R&D, the OECD aggregate includes the United States, the United Kingdom, France, Germany, Italy, Japan, and Canada. For some reason, the industry data for France and the United Kingdom are not available, so these countries are not included in the industry component.

Appendix C

Solving the Model Numerically

The transition dynamics of the optimal allocation can be studied as a system of six differential equations in six "state-like" variables that converge to constant values: s_t, ℓ_t, σ_t, δ_t, y_t, and z_t. These variables, their meaning, and their steady-state values are displayed in table C1.

Letting a "hat" denote a growth rate, the laws of motion for these state-like variables are

TABLE C1
KEY VARIABLES FOR STUDYING TRANSITION DYNAMICS

Variable	Meaning	Steady-State Value
s_t	Share of scientists in the consumption sector	$s^* = 0$
ℓ_t	Share of workers in the consumption sector	$\ell^* = 0$
σ_t	Scientists' share of the population	$\sigma^* = \frac{\alpha\lambda g_B}{\rho+(1-\phi+\alpha\beta)g_B}$
δ_t	Mortality rate	$\delta^* = 0$
$y_t \equiv g_{At}$	Growth rate of A_t	$y^* = g_A$
$z_t \equiv g_{Bt}$	Growth rate of B_t	$z^* = g_B$

$$
\begin{aligned}
\hat{s} &= \alpha z(1-\ell)\frac{\lambda}{1-\lambda}\cdot\frac{1-\sigma}{\sigma}\left(1-\frac{\ell}{1-\ell}\cdot\frac{1-s}{s}\cdot\frac{y}{z}\right),\\
\hat{\ell} &= \frac{\theta_\ell(\text{①} + \theta_\sigma\omega)}{1-\omega\gamma\theta_\sigma},\\
\hat{\sigma} &= \theta_\sigma(\text{②} + \gamma\hat{\ell}),\\
\hat{\delta} &= -\alpha\beta z + \beta\hat{\ell}\cdot\frac{\ell}{1-\ell} + \beta\hat{\sigma}\cdot\frac{\sigma}{1-\sigma},\\
\hat{y} &= \lambda(\bar{n} + \hat{s} + \hat{\sigma}) - (1-\phi)y,\\
\hat{z} &= \lambda\left(\bar{n} - \hat{s}\cdot\frac{s}{1-s} + \hat{\sigma}\right) - (1-\phi)y,
\end{aligned}
$$

where the following definitions have been used:

$$
\begin{aligned}
\theta_\ell &= \frac{1-\ell}{\gamma-(\gamma-1-\beta)\ell},\\
\theta_\sigma &= \frac{1}{1-\lambda+\dfrac{\gamma\sigma}{1-\sigma}},\\
\text{①} &= \alpha\beta z + \beta\delta\tilde{u}\cdot\frac{\ell}{1-\ell} - \rho - \delta - (\gamma-1)\alpha y,\\
\text{②} &= \rho + \delta + (1-\lambda)\hat{s}\cdot\frac{s}{1-s}\lambda\bar{n} + (\gamma-1)\alpha y - \frac{\alpha\lambda z(1-\ell)}{1-s}\cdot\frac{1-\sigma}{\sigma}.
\end{aligned}
$$

I solve the system of differential equations using "reverse shooting"; see Judd (1998, 355). That is, I start from the steady state, consider a small deviation, and then run time backward. To determine parameter values, I proceeded as follows.

1. To get the deviation from the steady state, I first select a mortality rate δ_T (I end up choosing $\delta_T = .0002$).

2. Next, I find the values of s_T and ℓ_T that minimize the distance between $\hat{s}_T$, $\hat{\ell}_T$, and $\hat{\sigma}_T$ from their BGP values—g_s for the first two and zero for $\hat{\sigma}$.

3. Given choices for the parameter values, I can then use the reverse shooting method to get a candidate path.

4. I use "fminsearch" in Matlab to find values for $\bar{u}$, β, γ, and λ that minimize the weighted sum of squared deviations between a selection of moments and a set of preferred values. These moments and values are given below:

a. Given a candidate path, we first find the year t^* such that $\tilde{u}(t^*)$ is the closest to 3.5. That is, we find the year in which the value of a year of life as a ratio to consumption is closest to 3.5. This corresponds, for example, to a value of a year of life of \$125,000 and a consumption per person of \$36,000, roughly consistent with the United States today.

b. Our first moment is $\tilde{u}(t^*)$ compared to 3.5.

c. Our second moment is $s(t^*)$ compared to 75 percent, motivated by figure 2, suggesting that around 25 percent of research is for health.

d. Our final moment is the growth rate of GDP in the year t^*, for which the target value is 2 percent.

5. Depending on the initial guess for these parameter values, this process finds different "local" optima, in part because the year t^* is free to move around. I changed the weights on the various moments and also considered different values of ϕ from the set $\{1/4, 1/2, 3/4, 5/6\}$ to hunt for the best overall fit. The results reported in the main text use the following parameter values: $\gamma = 2.6953$, $\beta = 0.6006$, $\bar{u} = .001$, $\lambda = .5377$, $\delta_T = .0002$, $\phi = 5/6$, $\rho = .02$, and $\alpha = 1$.

6. In general, two kinds of results emerged from this exercise. The first is what is shown in the main text, where the growth rate of A falls while the growth rate of B rises. For values of ϕ other than 5/6, one often finds values of $s(t^*)$ that were very close to one rather than close to 0.75. The other main dynamic that I found featured growth rates of A and B that started near zero and then rose over time. In these results, it was easy to get $s(t^*) \approx 0.75$ but was hard to get GDP growth around 2 percent in the same year.

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