Life and Growth

Charles I. Jones*
Stanford GSB and NBER

May 21, 2011 – Version 2.0

Abstract

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? 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.

*This paper was previously circulated under the title "The Costs of Economic Growth." I am grateful to Raj Chetty, Bob Hall, Peter Howitt, Pete Klenow, Omar Licandro, David Romer, Michele Tertilt, Martin Weitzman and participants in seminars at Berkeley, the Federal Reserve Bank of San Francisco, an NBER EFG meeting, Stanford, UC Irvine, and UCSD for comments, and to the National Science Foundation for financial support. Arthur Chiang, William Vijverberg and Mu-Jeung Yang provided excellent research assistance.

> *Certain events quite within the realm of possibility, such as a major asteroid collision, global bioterrorism, abrupt global warming — even certain lab accidents— could have unimaginably terrible consequences up to and including the extinction of the human race... I am not a Green, an alarmist, an apocalyptic visionary, a catastrophist, a Chicken Little, a Luddite, an anticapitalist, or even a pessimist. But... I have come to believe that what I shall be calling the "catastrophic risks" are real and growing...*
>
> — Richard A. Posner (2004, p. v)

1. Introduction

In October 1962, the Cuban missile crisis brought the world to the brink of a nuclear holocaust. President John F. Kennedy put the chance of nuclear war at "somewhere between one out of three and even." The historian Arthur Schlesinger, Jr., at the time an adviser of the President, later called this "the most dangerous moment in human history."[1] What if a substantial fraction of the world's population had been killed in a nuclear holocaust in the 1960s? In some sense, the overall cost of the technological innovations of the preceding 30 years would then seem to have outweighed the benefits.

While nuclear devastation represents a vivid example of the potential costs of technological change, it is by no means unique. The benefits from the internal combustion engine must be weighed against the costs associated with pollution and global warming. Biomedical advances have improved health substantially but made possible weaponized anthrax and lab-enhanced viruses. The potential benefits of nanotechnology stand beside the threat that a self-replicating machine could someday spin out of control. Experimental physics has brought us x-ray lithography techniques and superconductor technologies but also the remote possibility of devastating accidents as we smash particles together at ever higher energies. These

[1] For these quotations, see (Rees, 2003, p. 26).

and other technological dangers are detailed in a small but growing literature on so-called "existential risks"; Posner (2004) is likely the most familiar of these references, but see also Bostrom (2002), Joy (2000), Overbye (2008), and Rees (2003).

Technologies need not pose risks to the existence of humanity in order to have costs worth considering. New technologies come with risks as well as benefits. A new pesticide may turn out to be harmful to children. New drugs may have unforeseen side effects. Marie Curie's discovery of the new element radium led to many uses of the glow-in-the-dark material, including a medicinal additive to drinks and baths for supposed health benefits, wristwatches with luminous dials, and as makeup — at least until the dire health consequences of radioactivity were better understood. Other examples of new products that were intially thought to be safe or even healthy include thalidomide, lead paint, asbestos, and cigarettes.

While some new technologies are dangerous, many others are devoted to saving lives. Lichtenberg (2005), for example, estimates that new pharmaceuticals accounted for perhaps 40 percent of the rise in life expectancy between 1986 and 2000. MRI machines, better diagnostic equipment, and new surgical techniques as well as anti-lock brakes, airbags, and pollution scrubbers are all examples of life-saving technologies. How is growth theory altered when technologies involve life and death instead of just higher consumption?

Consider what might be called a "Russian roulette" theory of economic growth. Suppose the overwhelming majority of new ideas are beneficial and lead to growth in consumption. However, there is a tiny chance that a new idea will be particularly dangerous and cause massive 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 life-saving technologies?

The answers to these questions turn out to depend crucially on the shape of preferences. For a large class of conventional specifications, including log utility, safety eventually trumps economic growth. The optimal rate of 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. 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.

The paper is organized as follows. Section 2 presents a simple model that illustrates the main results. The advantage of this initial framework is its simplicity, which makes the basic intuition of the results apparent. The disadvantage is that the tradeoff between growth and safety is a black box. Section 3 then develops a rich idea-based endogenous growth model that permits a careful study of the mechanisms highlighted by the simple model. Section 4 discusses a range of empirical evidence that is helpful in judging the relevance of these results, and Section 5 concludes.

2. A Simple Model

At some level, this paper is about speed limits. You can drive your car slowly and safely, or fast and recklessly. Similarly, a key decision the economy must make is to set a safety threshold: researchers can introduce many new ideas without regard to safety, or they can select a very tight safety threshold and introduce fewer ideas each year, potentially slowing growth.

To develop this basic tradeoff, we begin with a simple two period OLG model. Suppose an individual's expected lifetime utility is

$$U = u(c_0) + e^{-\delta(g)} u(c), \quad c = c_0(1+g) \tag{1}$$

where c denotes consumption, g is the rate of consumption growth, and $\delta(g)$ is the mortality rate so $e^{-\delta(g)}$ is the probability an individual is alive in the second period. A new cohort of young people is born each period, and everyone alive at a point in time has the same consumption — this generation's $c_0(1+g)$ is the next generation's c_0.

To capture the "slow and safely or fast and recklessly" insight, assume $\delta(g)$ is an increasing function of the underlying rate of economic growth. Faster growth raises the mortality rate. In the richer model in the next section, this "black box" linking growth and mortality will be developed with much more care. Notice, however, that this approach incorporates the essential idea behind the Russian roulette example in the introduction.

Each generation when young chooses the growth rate for the economy to maximize their expected utility in equation (1). The growth rate balances the concerns for safety with the gains from higher consumption. The first order condition for this maximization problem can be expressed as

$$u'(c)c_0 = \delta'(g)u(c). \tag{2}$$

At the optimum, the marginal benefit from higher consumption growth, the left hand side, equals the marginal cost associated with a shorter life, the right hand side. This condition can be usefully rewritten as

$$1+g = \frac{\eta_{u,c}}{\delta'(g)} \tag{3}$$

where $\eta_{u,c}$ is the elasticity of $u(c)$ with respect to c.

To make more progress, assume the following functional forms (we'll generalize later):

$$\delta(g) = \delta g \tag{4}$$

$$u(c) = \bar{u} + \frac{c^{1-\gamma}}{1-\gamma}. \tag{5}$$

Utility takes the familiar form that features a constant elasticity of marginal utility;

the important role of the constant $\bar{u}$ will be discussed momentarily.

2.1. Exponential Growth: $0 < \gamma < 1$

To begin, let's assume $\gamma < 1$ and set $\bar{u} = 0$. In this case, the elasticity of utility with respect to consumption is $\eta_{u,c} = 1 - \gamma$, so the solution for growth in (3) is

$$g^* = \frac{1-\gamma}{\delta} - 1. \tag{6}$$

As long as δ is not too large, the model yields sustained positive growth over time. For example, if $\gamma = 1/2$ and $\delta = 1/10$, then $g^* = 4$ and $1 + g^* = 5$: consumption increases by a factor of 5 across each generation. This comes at the cost of a life expectancy that is less than the maximum, but such is the tradeoff inherent in this model.

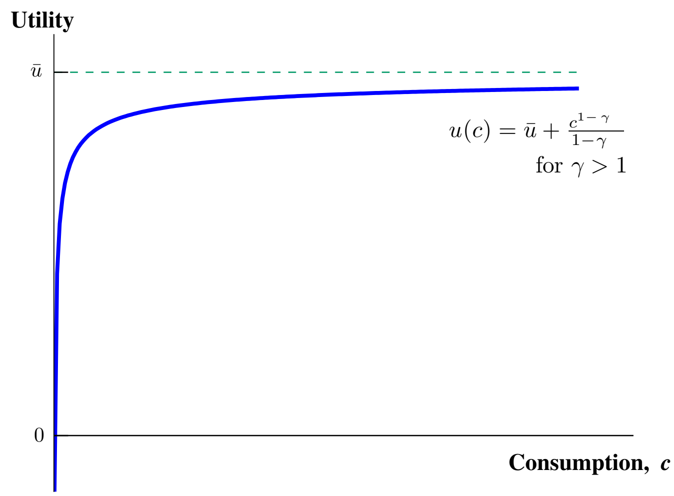
One can check that this conclusion is robust to letting $\bar{u} \neq 0$. In general, that will simply introduce transition dynamics into the model with $\gamma < 1$. The key elasticity $\eta_{u,c}$ then converges to $1 - \gamma$ as consumption gets large, leading to balanced growth as an asymptotic result.

2.2. The End of Growth: $\gamma > 1$

What comes next may seem a bit surprising. We've already seen that this simple model can generate sustained rapid growth for a conventional form of preferences. What we show now is that in the case where γ is larger than one, the model does not lead to sustained growth. Instead, concerns about safety lead growth to slow all the way to zero, at least eventually.

In this case, the constant $\bar{u}$ plays an essential role. In particular, notice that we've implicitly normalized the utility associated with "death" to be zero. For example, in (1), 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 the optimal choice at each point in time. With $\gamma > 1$, however, $\frac{c^{1-\gamma}}{1-\gamma}$ is less than zero. For example, this flow is $-1/c$ for $\gamma = 2$. An obvious way to make our problem

Figure 1: Flow Utility $u(c)$ for $\gamma > 1$



Note: Flow utility is bounded for $\gamma > 1$. If $\bar{u} = 0$, then flow utility is negative and dying is preferred to living.

interesting is to add a positive constant to flow utility. In this case, the flow utility function is shown in Figure 1. Notice that flow utility is bounded, and the value of $\bar{u}$ provides the upper bound.[2]

Assuming $\gamma > 1$ and $\bar{u} > 0$, the first order condition in (3) can be written as

$$(1+g)\left(\bar{u}c_0^{\gamma-1}(1+g)^{\gamma-1} + \frac{1}{1-\gamma}\right) = \frac{1}{\delta}. \quad (7)$$

The left-hand side of this expression is increasing in both c_0 and in g. As the economy gets richer over time and c_0 rises, then, it must be the case that g declines in order to satisfy this first order condition. The optimal rate of economic growth slows along the transition path.

In fact, one can see from this equation that consumption converges to a steady state with zero growth. According to the original first order condition in (3), the

[2]As the figure illustrates, there exists a value of consumption below which flow utility is still negative. Below this level, individuals would prefer death to life, so they would randomize between zero consumption and some higher value; see Rosen (1988). This level is very low for plausible 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, Philipson and Soares (2005), and Hall and Jones (2007).

steady state must be characterized by $\eta^*_{u,c} = \delta$ — that is, the point where the elasticity of the utility function with respect to consumption equals the mortality parameter. More explicitly, setting $g = 0$ in (7) reveals that the steady state value of consumption is given by

$$c^* = \left(\frac{1}{\bar{u}}\left(\frac{1}{\delta} + \frac{1}{\gamma - 1}\right)\right)^{\frac{1}{\gamma-1}}. \tag{8}$$

Because growth falls all the way to zero, mortality declines to zero as well and life expectancy is maximized.

To see the intuition for this result, recall the first order condition for growth: $1 + g = \eta_{u,c}/\delta$. When $\gamma > 1$ (or when flow utility is any bounded function), the marginal utility of consumption declines rapidly as the economy gets richer — that is, $\eta_{u,c}$ declines. This leads the optimal rate of growth to decline and the economy to converge to a steady state level of consumption.

A crucial implication of the bound on utility is that the marginal utility of consumption declines to zero rapidly. Consumption on any given day runs into sharp diminishing returns: think about the benefit of eating sushi for breakfast when you are already having it for lunch, dinner, and your midnight snack. Instead, obtaining extra days of life on which to enjoy your high consumption is a better way to increase utility.

This point can also be made with algebra. Consider the following expression:

$$\frac{u(c_t)}{u'(c_t)c_t} = \frac{1}{\eta_{u,c}} = \bar{u}c_t^{\gamma-1} + \frac{1}{1-\gamma}. \tag{9}$$

The left side of this equation is based on the flow value of an additional period of life, $u(c)$. We divide by the marginal utility of consumption to value this flow in units of consumption rather than in utils, so $u(c)/u'(c)$ is something like the value of a period of life in dollars. Then, we consider this value of life as a ratio to actual consumption.

The right side of this equation shows the value of life as a ratio to consumption under the assumed functional form for utility. Crucially, for $\gamma > 1$, the value of life rises faster than consumption. As the economy gets richer, concerns about safey become more important than consumption itself. This is the essential mechanism that leads the economy to tilt its allocation away from consumption growth and toward preserving life in the model.

2.3. Generalizing

More generally, it should be clear from equations (9) and (3) that this steady-state result would obtain with any (well-behaved) bounded utility function: in that case, the elasticity of utility with respect to consumption falls to zero as consumption goes to infinity, so the condition $\eta_{u,c} = \delta$ delivers a steady state.

Interestingly, this same result obtains with log utility. For $\gamma = 1$, we have $u(c) = \bar{u} + \log c$, and therefore $\eta_{u,c} = 1/u(c)$. The elasticity of utility still declines to zero as consumption gets arbitrarily large, leading to constant consumption in the long run, even though utility is unbounded.

Alternatively, consider changing the mortality function. If we instead assume $\delta(g) = \delta g^{\theta}$ with $\theta > 1$, then the simple model leads the growth rate to slow to zero, but only as consumption rises to infinity.[3] The implication that consumption will be constant in the long run, then, seems to be somewhat fragile. The more robust prediction is that safety considerations may lead consumption growth to slow to zero.

2.4. Summary of the Simple Model

This simple model is slighty more flexible than the "Russian roulette" example given in the introduction. Rather than choosing between stagnation and a fixed rate of growth with a small probability of death, the economy can vary the growth rate and the associated death rate smoothly. This death rate can be given two different interpretations. It may apply independently to each person in the population, so that

[3] The first order condition analogous to equation (3) becomes

$$g^{\theta-1}(1+g) = \frac{\eta_{u,c}}{\delta\theta}$$

which implies that $g \to 0$ only occurs as $\eta_{u,c} \to 0$ when $\gamma > 1$.

$e^{-\delta(g)}$ is the fraction of the population that survives to old age in each cohort. Alternatively, it may represent an existential risk that applies to the entire economy.

With $\gamma < 1$, the optimal tradeoff between growth and mortality leads to sustained exponential growth, albeit with some positive death rate. In the idiosyncratic interpretation of the death rate, life expectancy is simply less than its maximum but the economy continues forever. In the existential risk interpretation, the economy grows exponentially until, with probability one, the existential risk is realized and the economy comes to an end.

A very different result occurs when $\gamma \geq 1$, or more generally when flow utility is bounded. In this case, the marginal utility of consumption in any period falls rapidly as individuals get richer. In contrast, each additional year of life delivers a positive and growing amount of utility. The result is an income effect that favors safety over growth. The growth rate of the economy eventually falls to zero, life expectancy rises to its maximum, and consumption may even settle down to a constant. In the existential interpretation, the economy stops playing Russian roulette and, assuming it did not get unlucky before reaching the steady state, goes on forever.

3. Life and Growth in a Richer Setting

The simple model in the previous section is elegant and delivers clean results for the interaction between safety and growth. However, the way in which faster growth raises mortality is mechanical, and it is simply assumed that the economy can pick whatever growth rate it desires.

In this section, we 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 example, in this richer model, concerns for safety can slow the rate of exponential growth from 4% to 1%, for example, but will never lead to a steady-state level of consumption. While supporting the basic spirit of the simple model, then, the richer model illustrates some important ways in which the simple model may be misleading.

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, we posit a standard idea-based growth model where 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 life-saving sectors, and (ii) how many workers to put into using these ideas to manufacture goods.

A looser interpretation of the model goes like this. New technologies have consumption properties and life-related properties. Researchers must decide how much effort to put into each dimension. For instance, a new automobile engine can be made to be more powerful or to pollute less. Or researchers can spend their time making a new insulating material either safer or easier to manufacture.

3.1. The Economic Environment

The economy features two main sectors, a consumption sector and a life-saving 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, we'll 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 life-saving good H_t are given by

$$C_t = \left(\int_0^{A_t} x_{it}^{1/\alpha} di \right)^{\alpha} \text{ and } H_t = \left(\int_0^{B_t} z_{it}^{1/\alpha} di \right)^{\alpha}. \tag{10}$$

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 life-saving goods. It might be helpful to think of the z_{it} as purchases of different types of pharmaceuticals and surgical techniques. But we 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 safety regulations at construction sites.

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

$$\underbrace{\int_0^{A_t} x_{it} di}_{\equiv L_{ct}} + \underbrace{\int_0^{B_t} z_{it} di}_{\equiv L_{ht}} \leq L_t. \tag{11}$$

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

$$\dot{A}_t = \bar{a} S_{at}^{\lambda} A_t^{\phi} \text{ and } \dot{B}_t = \bar{b} S_{bt}^{\lambda} B_t^{\phi}, \tag{12}$$

where we assume $\phi < 1$. Once again, notice that we 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

$$S_{at} + S_{bt} \leq S_t \tag{13}$$

and

$$S_t + L_t \leq N_t. \tag{14}$$

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 of the life-saving sector.

Next, consider mortality. One component of mortality can be reduced by consuming life-saving goods:

$$\delta_t = h_t^{-\beta}, \quad h_t \equiv H_t/N_t. \tag{15}$$

Purchases of new drugs, better surgical techniques, pollution scrubbers, and seat-belts can save lives.

Total mortality is $\hat{\delta} + \delta_t$, which includes a parameter $\hat{\delta}$ that captures the fundamental underlying rate of mortality not susceptible to technological progress (which may or may not be zero). We assume an exogenous fertility rate of $\hat{n}$ and let $\bar{n} \equiv \hat{n} - \hat{\delta}$ denote the exogenous piece of population growth, apart from δ_t. Therefore the law of motion for population is

$$\dot{N}_t = (\bar{n} - \delta_t)N_t. \tag{16}$$

Finally, expected lifetime utility is given by

$$U = \int_0^\infty e^{-\rho t} u(c_t)\Lambda_t dt, \quad \dot{\Lambda}_t = -(\hat{\delta} + \delta_t)\Lambda_t \tag{17}$$

where

$$u(c_t) = \bar{u} + \frac{c_t^{1-\gamma}}{1-\gamma}, \quad c_t \equiv C_t/N_t. \tag{18}$$

Λ_t is the probability that an individual alive at date zero survives until date t; mortality reduces this survival probability. Flow utility takes a standard CRRA form, augmented by a constant $\bar{u}$, which is related, as earlier, to the overall value of life versus death.[4]

3.2. Allocating Resources

This economic environment features 14 unknowns — $C_t, H_t, c_t, h_t, A_t, B_t, x_{it}, z_{it}, S_{at}, S_{bt}, S_t, L_t, N_t, \delta_t$ — and 11 equations — equations (10) through (15), including the definitions for h_t and c_t (we are not counting lifetime utility and flow utility 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 life-saving ideas: $s_t \equiv S_{at}/S_t$.

2. How many workers make consumption goods versus life-saving 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 we will just impose this throughout the paper to simplify things.)

[4]As usual, ρ must be sufficiently large given growth so that utility is finite. We provide a precise version of this condition below.

3. How many people are scientists versus workers: $\sigma_t \equiv S_t/N_t$.

3.3. 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, we 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 0 and 1. That is, we consider putting a fixed fraction of our scientists in each research sector, a fixed fraction of our 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 0 and 1, there exists an asymptotic balanced growth path such that as $t \to \infty$, growth is given by*[5]

$$n^* = \bar{n}, \quad \delta^* = 0 \tag{19}$$

$$g_A^* = g_B^* = \frac{\lambda \bar{n}}{1-\phi} \tag{20}$$

$$g_c^* = g_h^* = \alpha g_A^* = \alpha g_B^* = \bar{g} \equiv \frac{\alpha \lambda \bar{n}}{1-\phi}. \tag{21}$$

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 $H_t = B_t^\alpha L_{ht}$. The idea production functions are also symmetric in form. For instance, $\frac{\dot{A}_t}{A_t} = \bar{a} S_{at}^\lambda / A_t^{1-\phi}$. So along a balanced growth path, 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 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...

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

The rule of thumb allocation suggests that this model will deliver a balanced growth path with life expectancy rising to its maximum. 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, we 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's not where we wish to go. For the moment, simply note that everything is nicely behaved and straightforward in the rule of thumb allocation.

3.4. The Optimal Allocation

Somewhat surprisingly, our 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 simple "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, we will put these interesting questions aside. Our 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 $c_t, h_t, s_t, \ell_t, \sigma_t, A_t, B_t, N_t, \delta_t$ that solves the following problem:

$$\max_{\{s_t,\ell_t,\sigma_t\}} U = \int_0^\infty N_t u(c_t) e^{-\rho t} dt \quad s.t. \tag{22}$$

$$c_t = A_t^{\alpha} \ell_t (1 - \sigma_t) \tag{23}$$

$$h_t = B_t^{\alpha} (1 - \ell_t)(1 - \sigma_t) \tag{24}$$

$$\dot{A}_t = \bar{a} s_t^{\lambda} \sigma_t^{\lambda} N_t^{\lambda} A_t^{\phi} \tag{25}$$

$$\dot{B}_t = \bar{b} (1 - s_t)^{\lambda} \sigma_t^{\lambda} N_t^{\lambda} B_t^{\phi} \tag{26}$$

$$\dot{N}_t = (\bar{n} - \delta_t) N_t, \quad \delta_t = h_t^{-\beta} \tag{27}$$

This can be viewed as the problem of maximizing the representative dynasty's utility function (e.g. by setting $N_0 = 1$), or it can be viewed as a social welfare function that gives equal weight to each live person's flow utility, regardless of age.

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

$$\mathcal{H} = N_t u(c_t) + p_{at} \bar{a} s_t^{\lambda} \sigma_t^{\lambda} N_t^{\lambda} A_t^{\phi} + p_{bt} \bar{b} (1 - s_t)^{\lambda} \sigma_t^{\lambda} N_t^{\lambda} B_t^{\phi} + v_t (\bar{n} - \delta_t) N_t, \tag{28}$$

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 life-saving idea, and an extra person 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 for this an the remaining propositions are given in the appendix).

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 balanced growth path such that as $t \to \infty$, the fraction of labor working in the consumption sector ℓ_t and the fraction of scientists making consumption ideas s_t both fall to zero at constant exponential rates, and asymptotic growth is given by*

$$g_s^* = g_\ell^* = \frac{-\bar{g}\,(\gamma - 1 - \beta)}{1 + (\gamma - 1)(1 + \frac{\alpha\lambda}{1-\phi})} < 0 \tag{29}$$

$$g_A^* = \frac{\lambda(\bar{n} + g_s^*)}{1 - \phi}, \quad g_B^* = \bar{g} \equiv \frac{\lambda \bar{n}}{1 - \phi} > g_A^* \tag{30}$$

$$g_\delta^* = -\beta\bar{g}, \quad g_h^* = \bar{g} \tag{31}$$

$$g_c^* = \alpha g_A^* + g_\ell^* = \bar{g}\cdot\frac{1+\beta(1+\frac{\alpha\lambda}{1-\phi})}{1+(\gamma-1)(1+\frac{\alpha\lambda}{1-\phi})} < \bar{g}. \tag{32}$$

This proposition echoes the key result from the simple "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 toy model, it was possible for consumption growth to cease, the more micro-founded model given here displays a more subtle result.

First, the economy optimally settles down to an asymptotic balanced growth path, but 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 (21) and the optimal allocation in (32): 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. In particular, 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 slows growth, recall the production functions for ideas

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

The share $1 - s_t$ in the life-saving sector converges to one, leading to the expected result that $g_B^* = \lambda\bar{n}/(1-\phi)$. However, the share s_t in the consumption ideas production function *falls* exponentially toward zero. The exponential shift of scientists out of this sector slows g_A relative to g_B, ultimately slowing consumption growth as well.

A very nice feature of this result is that it makes a clear prediction: we should see the composition of *research* shifting over time away from consumption ideas and toward life-saving ideas if the model is correct and if the marginal utility of consumption falls sufficiently fast. We will provide empirical evidence on this prediction later on in the paper.

To understand the underlying reason 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:

$$\frac{1-\ell_t}{\ell_t} = \beta \frac{\delta_t v_t}{u'(c_t)c_t} \tag{33}$$

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 life-saving 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, like the numerator.

In the analysis of this equation, it turns out to be useful to define $\tilde{v}_t \equiv \frac{v_t}{u'(c_t)c_t}$ — the value of a life in consumption units as a ratio to the level of consumption. The allocation of workers then depends on the product $\delta_t \tilde{v}_t$. In fact, as shown in the appendix, the allocation of scientists depends on exactly this same term — see equation (42).

Over time, the fraction 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 we've 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.

3.5. 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 balanced 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 life-saving ideas $\tilde{s}_t \equiv 1 - s_t$ both fall to zero at constant exponential rates, and asymptotic growth is given by*

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

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

and the exact values for $g_{\tilde{s}}^*$ and g_h^* depend on whether $\gamma > 1$ or $\gamma \leq 1$.

In particular, if $1 < \gamma < 1+\beta$:

$$g_{\tilde{s}}^* = g_{\tilde{\ell}}^* = \frac{-\bar{g}\,(\beta + 1 - \gamma)}{1 + \beta(1 + \frac{\alpha\lambda}{1-\phi})} < 0 \tag{34}$$

$$g_h^* = \bar{g} \cdot \left(\frac{1 + (\gamma - 1)(1 + \frac{\alpha\lambda}{1-\phi})}{1 + \beta(1 + \frac{\alpha\lambda}{1-\phi})} \right) < \bar{g}. \tag{35}$$

While if $\gamma \leq 1$:

$$g_{\tilde{s}}^* = g_{\tilde{\ell}}^* = \frac{-\beta\bar{g}}{1 + \beta(1 + \frac{\alpha\lambda}{1-\phi})} < 0 \tag{36}$$

$$g_h^* = \bar{g} \cdot \left(\frac{1}{1 + \beta(1 + \frac{\alpha\lambda}{1-\phi})} \right) < \bar{g}. \tag{37}$$

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 towards the consumption sector. In this case, the death rate falls faster than the value of life rises. Looking back at equation (33), 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.

3.6. "Interior" Growth when $1 < \gamma = 1 + \beta$

Proposition 4 (Optimal Growth with $1 < \gamma = 1 + \beta$): *Assume that the marginal utility of consumption falls rapidly ($\gamma > 1$) and 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 0 and 1, 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 where 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.[6]

3.7. Discussion

The simple toy model at the start of the paper and the richer model developed subsequently lead to slightly different conclusions. In the simple model, consumption growth falls to zero when the marginal utility of consumption diminishes rapidly, while in the richer model the growth rate 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 simple model, the mortality rate depends on the *growth rate* of the economy rather than on the level of technology in the life-saving sector, and this difference is evidently quite important. One can imagine a more sophisticated version of the simple model that would preserve its stronger results. For example — along the lines of the Russian roulette example from the introduction — suppose that most ideas are safe, but some ideas are dangerous and kill

[6] It turns out that even $\gamma = 1 + \beta$ is not enough to get balanced growth when $\gamma < 1$. In this case, all the workers and scientists still end up moving to the consumption sector, as in Proposition 3.

off a fraction of the population. If each idea raises consumption by a constant proportion (as in many Schumpeterian quality-ladder models like Aghion and Howitt (1992)), it seems likely that growth would optimally cease if the marginal utility of consumption falls rapidly.

The general result of this paper, then, is that concerns for safety can slow growth, with the precise nature of the slowdown depending on modeling details.

4. Empirical Evidence

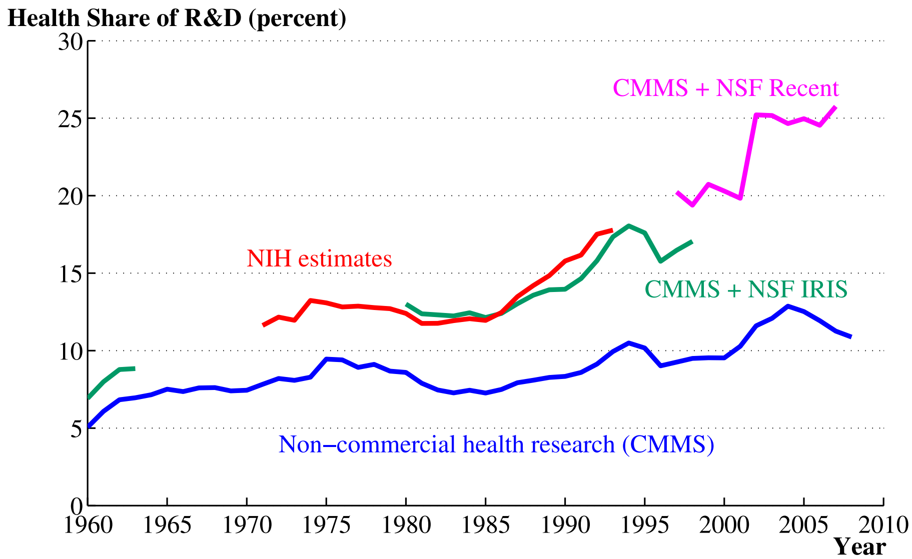
A useful feature of the main model in this paper is that it makes stark predictions regarding the composition of research. Depending on the relative magnitudes of $\gamma - 1$ and β, the direction of technical change should shift either toward or away from life-saving technologies. In particular, if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

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

4.1. The Composition of Research

One might think 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 because both the spending and performance of health research is done in several different organizations in the economy: industry, government, non-profits, 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

Figure 2: The Changing Composition of U.S. R&D Spending



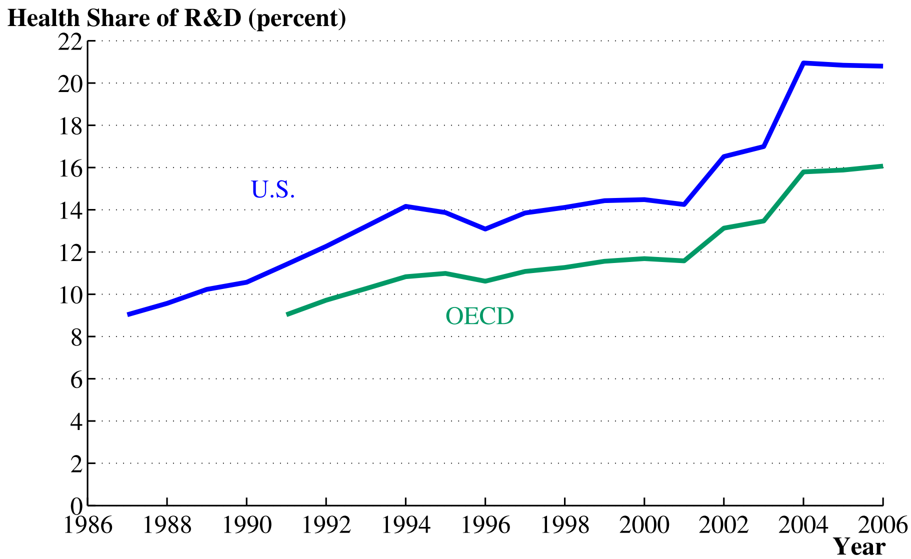
Note: The graph shows the rise in the share of R&D spending in the United States that is devoted to health, according to several different measures. See the Data Appendix for sources and methodology.

1970s and the early 1990s, the 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 twenty years.

As an imperfect substitute, I have put together some of the numbers myself. I'm far from an expert on these surveys, so the numbers I discuss below are surely imperfect and do not adequately address the concerns outlined above. For this reason, I do not report a single time series, but rather show results from a number of different calculations. Fortunately, these all strongly point in the same direction, so while we do not end up with a precise time series for health R&D, I think we do end up with consistent evidence that speaks to the topic of this paper.

The details of my calculations are discussed in the Data Appendix, and the results are provided in two figures. Figure 2 documents the changing composition of R&D spending in the United States. Four different time series are shown, including the original NIH estimates and a long time series on non-commercial health

Figure 3: The Changing Composition of OECD R&D Spending



Note: 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 the Data Appendix for sources and methodology.

research from the National Health Expenditure Accounts of the Centers for Medicare and Medicaid Services (CMMS). The remaining two time series add estimates of commercial research to the CMMS estimate, using two different collections of surveys by the National Science Foundation. The fact that the NIH series and the CMMS+NSF series coincide during overlapping years is somewhat reassuring.

The message from Figure 2 is quite clear. Whether we look at non-commericial 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.

Of course, life-saving 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. This data is only available since 1991 but tells 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.

This evidence on the composition of research is helpful in that it addresses one of the clear predictions of the model. Of course, this is not an entirely compelling test of the model, as there are other possible explanations for the changing composition of research. For example, perhaps the rise in the share of health spending in the economy is due to other factors, and health research is simply responding to these factors as well. Also, health research is an imperfect proxy for efforts devoted to life-saving technologies; research on pollution scrubbers and highway safety will not be included, for example.

4.2. Empirical Evidence on β

The parameter β is readily interpreted as the elasticity of the mortality rate with respect to real health expenditures. A plausible upper bound for this parameter can then be obtained by considering the relative trends in mortality and health spending: this calculation would attribute *all* the decline in mortality to health spending, which is surely an overestimate given the likely importance of other factors.

According to *Health, United States 2009*, age-adjusted mortality rates fell at an average annual rate of 1.2% between 1960 and 2007, while CPI-deflated health spending rose at an average annual rate of 4.1%.[7] The ratio of these two growth rates gives an estimate of the upper bound for β of 0.291. Hall and Jones (2007) conduct a more formal analysis along these lines using age-specific mortality rates, 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.

---

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

4.3. Estimates of γ

Given the upper bound for β just reported, life considerations will dominate in the model if γ is larger than about 1.3. In the most common 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, supported by 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, Juster, Kimball and Shapiro (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.

4.4. 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, Costa and Kahn (2004) and Hammitt, Liu and Liu (2000) 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 $\gamma > 1.3$.

4.5. 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.

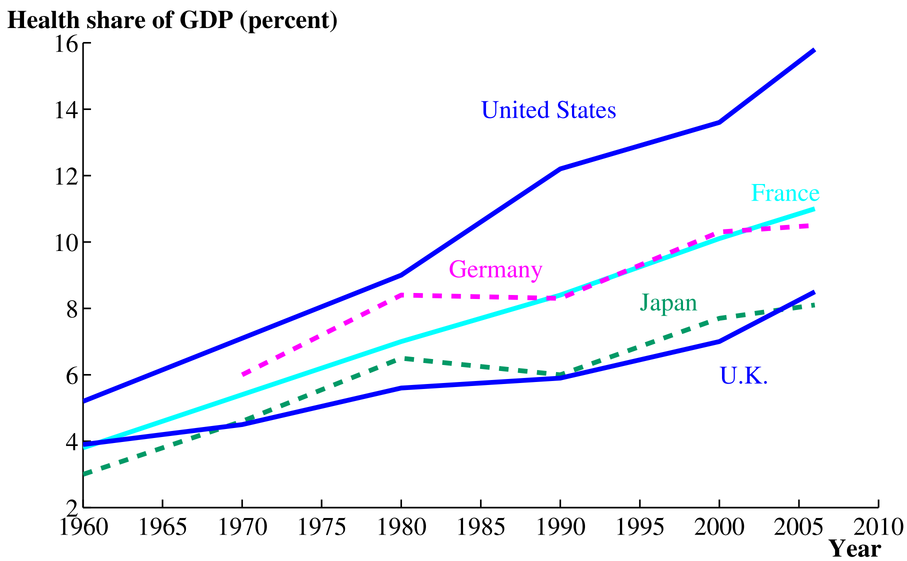
What evidence is there for an income elasticity of health spending larger than one? Figure 4 shows some international evidence. Health spending as a share of GDP is rising in many countries of the world, not only in the United States. Indeed, for the 19 OECD countries reporting data in both 1970 and 2006 (many not shown), all experienced a rising health share.

Acemoglu, Finkelstein and Notowidigdo (2009a) 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. 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).

4.6. Growth in Health and Non-Health 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 life-saving sector. Moreover, at least insofar as the parameters of the idea production function

Figure 4: International Evidence on the Income Effect in Health Spending



Note: Data are from *OECD Health Data 2009* and are reported every 10 years, except for the last observation from 2006.

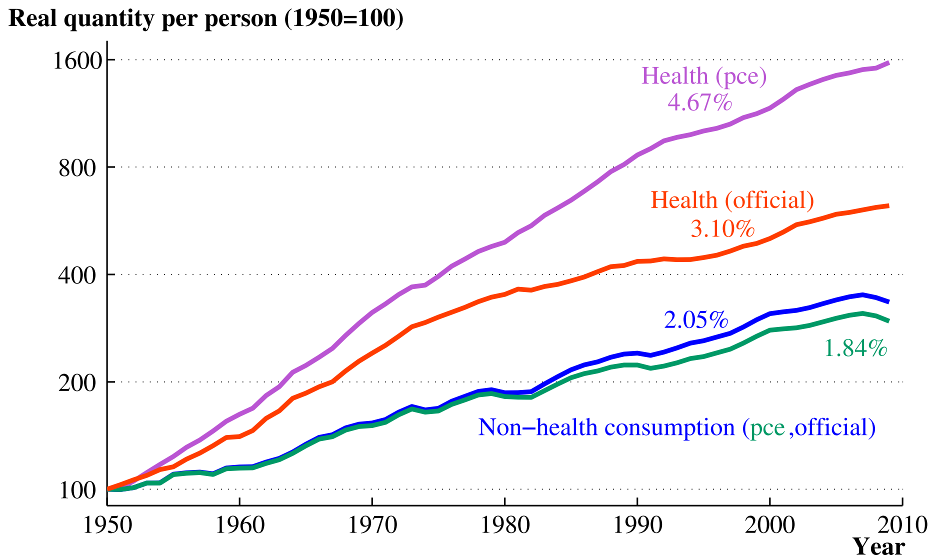
are similar in those two sectors (and we have no real evidence pushing us one way or the other on this), the sector that sheds its researchers will grow more slowly in the long run.

This prediction prompts us to look at the historical evidence on the growth of per capita consumption for both the health and non-health sectors, respectively. Figure 5 shows this evidence, taken from the National Income and Product Accounts 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 BEA deflators for health and non-health 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

Figure 5: Health and Consumption



Note: The plot shows real per capita consumption expenditures for health and non-health 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).

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.[8] The "pce" measures in Figure 5 therefore deflate both nominal health spending and

[8]Cutler, McClellan, Newhouse and Remler (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, Bir, Busch, Frank and Normand (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) obtain similar results using a structural model and more aggregate data.

nominal consumption spending by the overall NIPA deflator for personal consumption expenditures, implicitly assuming 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% per year between 1950 and 2009, versus only 1.84% for per capita consumption.

If the economy were already in steady state, the growth rates reported in Figure 5 would be direct evidence on the magnitude of the "growth drag" associated with life considerations, and this drag is substantial: $1.84/4.67 \approx 0.4$, for example, suggesting that consumption growth is reduced to only 40% of its feasible rate because of the rising importance of life.

Unfortunately, the evidence on the composition of research suggests the economy is far from its steady state, since the research share is well below one. This evidence on the growth drag, then, is only suggestive. However, 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.

4.7. Calibrating the Growth Drag

We have discussed a range of evidence in this section — the shift in the composition of research 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 non-health consumption. While none is entirely decisive, the evidence suggests that the possibility of an income effect favoring life-saving technologies should be considered carefully. The case studied in Proposition 2 where $\gamma - 1 > \beta$ may be the relevant one.

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

$$g_h^* = \frac{\alpha\lambda\bar{n}}{1-\phi} = \bar{g} \tag{38}$$

$$g_c^* = \bar{g} \cdot \frac{1+\beta(1+\frac{\alpha\lambda}{1-\phi})}{1+(\gamma-1)(1+\frac{\alpha\lambda}{1-\phi})} < \bar{g}. \tag{39}$$

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 $\frac{\alpha\lambda}{1-\phi}$. We've already discussed evidence on the first two of these above. Notice from equation (38) 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 (39). 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% of its feasible rate in the optimal allocation. It would be feasible to keep the research shares constant and let consumption grow much faster, but the rising value of life means this is not optimal.

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.

Table 1: The Growth Drag

	$\beta = .25$		$\beta = .10$	
$\frac{\alpha\lambda}{1-\phi}$	$\gamma = 1.5$	$\gamma = 2$	$\gamma = 1.5$	$\gamma = 2$
0.50	0.79	0.55	0.66	0.46
1.00	0.75	0.50	0.60	0.40
2.00	0.70	0.44	0.52	0.33

Note: The table reports the ratio of g_c to g_h in 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 $\frac{1+\beta(1+\frac{\alpha\lambda}{1-\phi})}{1+(\gamma-1)(1+\frac{\alpha\lambda}{1-\phi})}$. The mean across the various estimates is 0.56.

4.8. A Future Growth Slowdown?

Close to the balanced growth path, the share of research devoted to health would be close to one, so that the percentage increases in the health research share would be small and not contribute significantly to growth. In contrast, the percentage declines in the consumption research share would be large, significantly slowing growth in that sector. In recent decades, however, the economy appears to be far enough from steady state that the opposite is still occuring: a growing health research share boosts growth in that sector. Similarly, the percentage decline in the consumption share of research is relatively modest, which means that consumption is growing faster than its long run rate.

To get a rough sense of the magnitudes involve, recall that the health share of research in Figure 2 is estimated to have risen from about 7% to about 25% between 1960 and 2007. This corresponds to an average annual growth rate of about 2.7%, which is large relative to the overall growth rate of R&D. In constrast, the consumption research share has fallen from 93% to 75% over the same period, corresponding to an average annual growth rate of -0.46%. This is more in line with calibrated values of the long-run decline in the consumption research share.

The implication of this argument is that some of the hypothetical growth drag that we have calculated applies to *future* growth, particularly in terms of the production of life-saving goods. That is, this channel provides a mechanism through which health spending growth — which makes up an increasing portion of GDP growth — would be predicted to slow in the future. The magnitudes computed for the growth drags suggest that this slowdown could be substantial.

4.9. Sustainable Growth and the Environment

This paper is also related to the literature on sustainable growth and the environment; for example, see Solow (1974), Stiglitz (1974), Gradus and Smulders (1993), and Aghion and Howitt (1998, Ch. 5). Particularly relevant are Stokey (1998) and Brock and Taylor (2005), who study the environmental Kuznets curve in which pollution first rises and then falls with economic development. 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: growth is slower than it would otherwise be because of environmental concerns. While the key issues here are very distinct — the utility costs of pollution in one case versus the loss of life associated with dangerous technologies in the other — it is interesting that the curvature of marginal utility plays a central role in both and can slow growth.

One of the ways in which pollution has been mitigated in the United States is through the development of new, cleaner technologies. Examples include scrubbers that remove harmful particulates from industrial exhaust and catalytic converters that reduce automobile emissions. Researchers can spend their time making existing technologies safer or inventing new technologies. Rising concerns for safety lead them to divert effort away from new technologies, which may slow growth. Acemoglu, Aghion, Bursztyn and Hemous (2009b) explore this kind of directed technical change in a model of growth and the environment.

5. 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 and then in a richer model in which growth explicitly depends on the discovery of new ideas. 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 growth to slow to zero, even potentially leading to a steady-state level of consumption.

The intuition for the slowing of growth 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 growth slow down.

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 income and 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.

A Appendix: Derivations and Proofs

This appendix contains outlines of the proofs of the propositions reported in the paper.

As a prelude to these propositions, we first consider the optimal allocation problem in equations (22) through (27). Using the Hamiltonian in (28) and applying the Maximum Principle, the first-order necessary conditions for a solution are

$$\frac{1-s_t}{s_t} = \frac{p_{bt}\dot{B}_t}{p_{at}\dot{A}_t} \tag{FOC: s}$$

$$\frac{1-\ell_t}{\ell_t} = \beta\delta_t \cdot \frac{v_t}{u'(c_t)c_t} \tag{FOC: ℓ}$$

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

$$\rho = \frac{\dot{v}_t}{v_t} + \frac{1}{v_t}\left[u(c_t) + p_{at}\lambda\frac{\dot{A}_t}{N_t} + p_{bt}\lambda\frac{\dot{B}_t}{N_t} + v_t(\bar{n} - \delta_t)\right] \tag{FOC: N}$$

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

$$\rho = \frac{\dot{p}_{bt}}{p_{bt}} + \frac{1}{p_{bt}}\left[p_{bt}\phi\frac{\dot{B}_t}{B_t} + \alpha\beta v_t N_t\frac{\delta_t}{B_t}\right] \tag{FOC: B}$$

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, we 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

$$p_{at} = \frac{\alpha N_t u'(c_t)c_t/A_t}{\rho - g_{p_a t} - \phi g_{At}} \text{ and } p_{bt} = \frac{\alpha\beta N_t v_t \delta_t/B_t}{\rho - g_{p_b t} - \phi g_{Bt}}. \tag{40}$$

   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

$$\frac{p_{bt}B_t}{p_{at}A_t} = \beta\delta_t\tilde{v}_t \cdot \frac{\rho - g_{p_a t} - \phi g_{At}}{\rho - g_{p_b t} - \phi g_{Bt}}. \tag{41}$$

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

$$\frac{1-s_t}{s_t} = \beta\delta_t\tilde{v}_t \cdot \frac{\rho - g_{p_a t} - \phi g_{At}}{\rho - g_{p_b t} - \phi g_{Bt}} \cdot \frac{g_{Bt}}{g_{At}}. \tag{42}$$

   Recall from (FOC: ℓ) that $\frac{1-\ell_t}{\ell_t} = \beta\delta_t\tilde{v}_t$, 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, we study $\tilde{v}_t$. Using (FOC: N) and (40), we obtain

$$\tilde{v}_t = \frac{\frac{u(c_t)}{u'(c_t)c_t} + \frac{\alpha\lambda g_{At}}{\rho - g_{p_a t} - \phi g_{At}}}{\rho - g_{vt} - n_t - \frac{\alpha\lambda\beta g_{Bt}\delta_t}{\rho - g_{p_b t} - \phi g_{Bt}}}. \tag{43}$$

   This is a key expression: the value of having an extra person in the economy (as a ratio to consumption) depends crucially on the extra utility that person enjoys — that's the first term in the numerator and the one that matters most in what follows. The second term in the numerator reflects the additional consumption ideas that an extra person will generate. The denominator essentially converts this flow dividend (the numerator) into a present discounted value. Notice that the discount rate is reduced by the additional health ideas that the person will generate, which lets the person live longer to enjoy more utility and produce even more ideas in the future.

4. Now recall that given our CRRA 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 balanced growth path where $c_t \to \infty$,

$$g_{\tilde{v}} = (\gamma - 1)g_c. \tag{44}$$

5. Now let's guess that the solution for the asymptotic balanced growth path takes the following form: s_t and ℓ_t fall toward zero at a constant exponential rate, while $\sigma_t \to \sigma^*$ and $n_t \to \bar{n}$. We'll see that the key condition delivering this result will be $\gamma > 1 + \beta$.

6. Under this proposed solution, consumption growth is

$$g_c = \alpha g_A + g_\ell = \alpha g_A + g_s \tag{45}$$

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 (42) 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 $\dot{A}_t = \bar{a}s_t^\lambda \sigma_t^\lambda N_t^\lambda A_t^\phi$ and $\dot{B}_t = \bar{b}(1-s_t)^\lambda \sigma_t^\lambda N_t^\lambda B_t^\phi$. 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

$$g_A = \frac{\lambda(\bar{n} + g_s)}{1-\phi} \text{ and } g_B = \frac{\lambda \bar{n}}{1-\phi}. \tag{46}$$

8. Combining (44), (45), and (46), gives

$$g_{\tilde{v}} = (\gamma - 1)\left(\frac{\alpha\lambda(\bar{n} + g_s)}{1-\phi} + g_s\right). \tag{47}$$

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 $\sigma_t \to \sigma^*$,

$$g_\delta = -\alpha\beta g_B. \tag{48}$$

10. Now, finally, look back at (42) and consider the asymptotic growth rate of each side of the equation. Along our proposed balanced growth path, $1 - s_t$ 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 our last two results in (47) and (48), taking growth rates of (42) gives

$$-g_s = -\alpha\beta g_B + (\gamma - 1)\left(\frac{\alpha\lambda(\bar{n} + g_s)}{1-\phi} + g_s\right). \tag{49}$$

Solving for g_s then gives

$$g_s = \frac{-\alpha g_B(\gamma - 1 - \beta)}{1 + (\gamma-1)(1 + \frac{\alpha\lambda}{1-\phi})}. \tag{50}$$

Under our key assumption that $\gamma > 1 + \beta$, this solution for g_s is negative, as we 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

$$\frac{\sigma^*}{1-\sigma^*} = \frac{\alpha\lambda g_B}{\rho - g_{p_b} - \phi g_B} \tag{51}$$

where, from (40), $g_{p_b} = \bar{n} - g_s + (\gamma - 1)g_c > 0$. This means that for the denominator in (51) to be positive, we require

$$\rho - \bar{n} + g_s - (\gamma - 1)g_c - \phi g_B > 0, \tag{52}$$

which, given the solutions for g_s, g_c, and g_B implicitly provides the condition on ρ needed for utility to be finite and for this general problem to be well-defined.

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 through 3 are identical.

4. Here things start to change, depending on whether $\gamma \leq 1$ 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 $\gamma \leq 1$, 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, we will focus on the $\gamma > 1$ case below, so that
$$g_{\tilde{v}} = (\gamma - 1)g_c. \tag{53}$$
(To consider the case where $\gamma < 1$, simply replace the $(\gamma - 1)$ terms below with a zero, reflecting the appropriate value of $g_{\tilde{v}}$.)

5. Now we guess that the solution for the asymptotic balanced growth path 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 $\sigma_t \to \sigma^*$ and $n_t \to \bar{n}$. 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
$$g_c = \alpha g_A \tag{54}$$
while growth of the life-saving aggregate is
$$g_h = \alpha g_B + g_{\tilde{\ell}} = \alpha g_B + g_{\tilde{s}}. \tag{55}$$

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 (42) above. In fact, it is helpful to repeat that equation here, written in terms of the tilde variables:

$$\frac{\tilde{s}_t}{1-\tilde{s}_t} = \beta\delta_t\tilde{v}_t \cdot \frac{\rho - g_{p_a t} - \phi g_{At}}{\rho - g_{p_b t} - \phi g_{Bt}} \cdot \frac{g_{Bt}}{g_{At}}. \tag{56}$$

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 $\dot{A}_t = \bar{a}(1-\tilde{s}_t)^\lambda \sigma_t^\lambda N_t^\lambda A_t^\phi$ and $\dot{B}_t = \bar{b}\tilde{s}_t^\lambda \sigma_t^\lambda N_t^\lambda B_t^\phi$. 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
$$g_A = \frac{\lambda\bar{n}}{1-\phi} \text{ and } g_B = \frac{\lambda(\bar{n}+g_{\tilde{s}})}{1-\phi}. \tag{57}$$

8. Combining (53), (54), and (57), gives
$$g_{\tilde{v}} = (\gamma-1)\bar{g}. \tag{58}$$

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
$$g_\delta = -\beta\left(\frac{\alpha\lambda(\bar{n}+g_{\tilde{s}})}{1-\phi} + g_{\tilde{s}}\right). \tag{59}$$

   Combining (58) and (59) leads to
$$g_\delta + g_{\tilde{v}} = -(1+\beta-\gamma)\bar{g} - \beta g_{\tilde{s}}\left(1 + \frac{\alpha\lambda}{1-\phi}\right). \tag{60}$$

10. Now, look back at (56) and consider the asymptotic growth rate of each side of the equation. Along our proposed balanced growth path, $1-\tilde{s}_t$ 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 (58), (59), and (60) gives

$$g_{\tilde{s}} = -(\beta + 1 - \gamma)\bar{g} - \beta g_{\tilde{s}} \left(1 + \frac{\alpha\lambda}{1-\phi}\right). \tag{61}$$

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

$$g_{\tilde{s}} = \frac{-\bar{g}\,(\beta + 1 - \gamma)}{1 + \beta(1 + \frac{\alpha\lambda}{1-\phi})}. \tag{62}$$

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 (55) then gives the growth rate of the life-saving aggregate:

$$g_h^* = \bar{g} \cdot \left(\frac{1 + (\gamma - 1)(1 + \frac{\alpha\lambda}{1-\phi})}{1 + \beta(1 + \frac{\alpha\lambda}{1-\phi})} \right) < \bar{g}. \tag{63}$$

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

The proof here is straightforward and follows from the earlier proofs. For example, since $\gamma = 1 + \beta$, one can see from equation (50) that $g_s = 0$. The key growth rates of the economy are then equal to $\bar{g}$ immediately.

B Data Appendix

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 U.S. data and the other using OECD data. These are discussed in turn.

B1. United States

Several main sources are used to construct the US data underlying Figure 2. A spreadsheet available from the data section of my web page called NSF-AllYears-IndustrialRND.xls contains the detailed calculations.

First, for the years 1971 to 1993, 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, we use the NIH Data Books for 1982, 1989, and 1994, splicing together these series during overlapping years to construct our 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.

Our 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. 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 only includes non-commercial 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 non-profit 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 IRIS data, 1953–1998, Table H-25. From this source, we obtain "Company and other (except Federal) funds for industrial R&D performance, by industry" for 1953–1998. In particular, we sum three industries to get commercial health research: "drugs and medicines" (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 our next source.
- National Science Foundation, Research and Development in 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 NAICS industry classification. We 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 this data.

- Finally, total spending on R&D is obtained from the National Science Foundations, National Patterns of R&D Resources: 2008 Data Update, which reports data for 1953–2008.

Notice that our measures of commericial/industry R&D exclude federal funds but do include non-profit 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.

B2. OECD

The OECD (and US) data underlying Figure 3 are taken from the OECD iLibrary. A spreadsheet available from the data section of my web page called STAN-HealthRND.xls contains the detailed calculations.

Two sets of data from the OECD iLibrary are used:

- Government budget appropriations or outlays for RD: This source provides government spending on R&D for health and overall from 1981 to 2007 in current PPP-adjusted US dollars.
- STAN R&D Expenditure in Industry (ISIC Rev. 3) ANBERD ed2009: This source provides spending on R&D by industry. Because of a relatively limited industry breakdown, our 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 arbitary but was suggested by calculations using the U.S. sources discussed earlier.

From this data, we calculate the health share of R&D for both the United States and for a set of OECD countries. For government R&D, our 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.

References

Acemoglu, Daron, "Directed Technical Change," *Review of Economic Studies*, October 2002, *69* (4), 781–810.

—, Amy Finkelstein, and Matthew J. Notowidigdo, "Income and Health Spending: Evidence from Oil Price Shocks," 2009. MIT working paper.

— and Simon Johnson, "Disease and development: the Effect of Life Expectancy on Economic Growth," *Journal of Political Economy*, 2007, *115* (6), 925–985.

—, Philippe Aghion, Leonardo Bursztyn, and David Hemous, "The Environment and Directed Technological Change," 2009. MIT working paper.

Aghion, Philippe and Peter Howitt, "A Model of Growth through Creative Destruction," *Econometrica*, March 1992, *60* (2), 323–351.

— and —, *Endogenous Growth Theory*, Cambridge, MA: MIT Press, 1998.

Ashenfelter, Orley and Michael Greenstone, "Using Mandated Speed Limits to Measure the Value of a Statistical Life," *Journal of Political Economy*, February 2004, *112* (1), S226–S267. Part 2.

Attanasio, Orazio P. and Guglielmo Weber, "Is Consumption Growth Consistent with Intertemporal Optimization? Evidence from the Consumer Expenditure Survey," *Journal of Political Economy*, 1995, *103* (6), 1121–1157.

Barsky, R.B., F.T. Juster, M.S. Kimball, and M.D. Shapiro, "Preference Parameters and Behavioral Heterogeneity: An Experimental Approach in the Health and Retirement Study," *Quarterly Journal of Economics*, 1997, *112* (2), 537–579.

Becker, Gary S., Tomas J. Philipson, and Rodrigo R. Soares, "The Quantity and Quality of Life and the Evolution of World Inequality," *American Economic Review*, March 2005, *95* (1), 277–291.

Berndt, Ernst R., Anupa Bir, Susan H. Busch, Richard G. Frank, and Shaon-Lise T. Normand, "The Medical Treatment of Depression, 1991–1996: Productive Inefficiency, Expected Outcome Variations, and Price Indexes," 2000. NBER Working Paper No. 7816.

Bostrom, Nick, "Existential Risks," *Journal of Evolution and Technology*, March 2002, *9*.

Brock, William and M. Scott Taylor, "Economic Growth Theory and the Environment: A Review of Theory and Empirics," *Handbook of Economic Growth*, 2005, pp. 1749–1821.

Chetty, Raj, "A New Method of Estimating Risk Aversion," *American Economic Review*, December 2006, *96* (5), 1821–1834.

Costa, Dora L. and Matthew E. Kahn, "Changes in the Value of Life, 1940–1980," *Journal of Risk and Uncertainty*, September 2004, *29* (2), 159–180.

Cutler, David M., Mark B. McClellan, Joseph P. Newhouse, and Dahlia Remler, "Are Medical Prices Declining? Evidence from Heart Attack Treatments," *Quarterly Journal of Economics*, November 1998, *113* (4), 991–1024.

Ehrlich, Isaac and Hiroyuki Chuma, "A Model of the Demand for Longevity and the Value of Life Extension," *Journal of Political Economy*, August 1990, *98* (4), 761–782.

Gradus, Raymond and Sjak Smulders, "The Trade-off between Environmental Care and Long-Term GrowthPollution in Three Prototype Growth Models," *Journal of Economics*, 1993, *58* (1), 25–51.

Grossman, Michael, "On the Concept of Health Capital and the Demand for Health," *Journal of Political Economy*, March/April 1972, *80* (2), 223–255.

Gruber, Jonathan, "A Tax-Based Estimate of the Elasticity of Intertemporal Substitution," 2006. NBER Working Paper 11945.

Guvenen, Fatih, "ReconcilinG Conflicting Evidence on the Elasticity of Intertemporal Substitution: A Macroeconomic Perspective," *Journal of Monetary Economics*, 2006, *53* (7), 1451–1472.

Hall, Robert E., "Intertemporal Substitution in Consumption," *Journal of Political Economy*, April 1988, *96* (2), 339–357.

—, "Reconciling Cyclical Movements in the Marginal Value of Time and the Marginal Product of Labor," *Journal of Political Economy*, 2009, *117* (2), 281–323.

— and Charles I. Jones, "The Value of Life and the Rise in Health Spending," *Quarterly Journal of Economics*, February 2007, *122* (1), 39–72.

Hammitt, James K., Jin-Tan Liu, and Jin-Long Liu, "Survival is a Luxury Good: The Increasing Value of a Statistical Life," July 2000. Harvard University mimeo.

Jones, Charles I., "R&D-Based Models of Economic Growth," *Journal of Political Economy*, August 1995, *103* (4), 759–784.

— and Paul M. Romer, "The New Kaldor Facts: Ideas, Institutions, Population, and Human Capital," *American Economic Journal: Macroeconomics*, January 2010, *2* (1), 224–245.

Joy, Bill, "Why the World Doesn't Need Us," *Wired Magazine*, April 2000, *8* (4).

Lawver, Daniel, "Measuring Quality Increases in the Medical Sector," 2011. A.S.U. manuscript.

Lichtenberg, Frank, "The Impact of New Drug Launches on Longevity: Evidence from Longitudinal, Disease-Level Data from 52 Countries, 1982–2001," *International Journal of Health Care Finance and Economics*, January 2005, *5* (1), 47–73.

Lucas, Deborah, "Asset Pricing with Undiversifiable Risk and Short Sales Constraints: Deepening the Equity Premium Puzzle," *Journal of Monetary Economics*, 1994, *34* (3), 325–342.

Malani, Anup and Tomas J. Philipson, "Can Medical Progress be Sustained? Implications of the Link Between Development and Output Markets," Working Paper 17011, National Bureau of Economic Research May 2011.

Murphy, Kevin M. and Robert H. Topel, "The Value of Health and Longevity," *Journal of Political Economy*, October 2006, *114* (5), 871–904.

— and Robert Topel, "The Economic Value of Medical Research." In *Measuring the Gains from Medical Research: An Economic Approach* Murphy and Topel, eds (2003).

— and — , eds, *Measuring the Gains from Medical Research: An Economic Approach*, Chicago: University of Chicago Press, 2003.

Nordhaus, William D., "The Health of Nations: The Contribution of Improved Health to Living Standards." In Murphy and Topel, eds (2003) pp. 9–40.

Overbye, Dennis, "Gauging a Collider's Odds of Creating a Black Hole," *New York Times*, April 2008.

Posner, Richard A., *Catastrophe: Risk and Response*, Oxford University Press, 2004.

Rees, Martin, *Our Final Century*, London: William Heinemann, 2003.

Romer, Paul M., "Endogenous Technological Change," *Journal of Political Economy*, October 1990, *98* (5), S71–S102.

Rosen, Sherwin, "The Value of Changes in Life Expectancy," *Journal of Risk and Uncertainty*, 1988, *1*, 285–304.

Shapiro, Irving, Matthew D. Shapiro, and David W. Wilcox, "Measuring the Value of Cataract Surgery," 1999. University of Michigan mimeo.

Solow, Robert M., "Intergenerational Equity and Exhaustible Resources," *Review of Economic Studies*, 1974, pp. 29–45.

Stiglitz, Joseph, "Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths," *Review of Economic Studies*, 1974, pp. 123–137.

Stokey, Nancy L., "Are there Limits to Growth?," *International Economic Review*, 1998, pp. 1–31.

Triplett, Jack E. and Barry P. Bosworth, "Productivity in the Services Sector," 2000. Brookings Institution mimeo.

Viscusi, W. Kip and Joseph E. Aldy, "The Value of a Statistical Life: A Critical Review of Market Estimates throughout the World," *Journal of Risk and Uncertainty*, 2003, *27*, 5–76.

Vissing-Jorgensen, Annette and Orazio P. Attanasio, "Stock-Market Participation, Intertemporal Substitution, and Risk-Aversion," *American Economic Association Papers and Proceedings*, May 2003, *93* (2), 383–391.

Weisbrod, Burton A., "The Health Care Quadrilemma: An Essay on Technological Change, Insurance, Quality of Care, and Cost Containment," *Journal of Economic Literature*, June 1991, *29*, 523–552.