The Economics of Has-beens

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The evolution of technology causes human capital to become obsolete. We study this phenomenon in an overlapping generations setting, assuming that technology evolves stochastically and that older workers find updating uneconomic. Experience and learning by doing may offer the old some income protection, but technology advance always turns them into has-beens to some degree. We focus on the determinants (demand elasticities, persistence of technology change, etc.) of the severity of the has-beens effect. It can be large, even leading to negatively sloped within-occupation age-earnings profiles and an occupation dominated by a few young, high-income workers. Architecture displays the sort of features the theory identifies as magnifying the has-beens effect, and both anecdotes and some data suggest that the has-beens effect in architecture is extreme indeed.

I. Introduction

Human capital investments, like other types of investments, are risky. That is, when an individual makes an investment in human capital, factors beyond his or her control will affect the value ultimately accruing

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to the investment. A particularly important factor of this kind is the evolution of technology. And the possibility that technological change will affect the value of human capital investments will influence the choice of which kind of human capital to acquire ex ante and, subsequently, will affect entry into occupations and workers' incomes.

Consider, for example, the market for architects. Advances in computing have revolutionized the field, increasing the art component in what had traditionally been a blend of art, engineering, and drafting. This drastically lowered the cost of design development and reduced the cost of experimentation or modification of plans even more. Older architects have found it uneconomic to master the complex computer skills that enable the young to produce architectural services so easily and flexibly and have found hiring a "computer department" to be a poor substitute. Thus these advances have allowed younger architects to serve much of the market for architectural services, causing the older generation to lose much of its business.[1] For example, according to the 1990 Census of Population and Housing, white architects (engineers and surveyors are included here too) with bachelor's degrees, aged 25–34, earned an average of more than $130,000 in 1989, whereas those aged 45–54 earned just over $100,000. The corresponding numbers for lawyers and judges, for whom practice and experience foster understanding of new laws, court decisions, and so forth, are roughly $42,000 and just over $82,000.

In this paper we develop a simple model of technology-specific human capital investment and study the impact of stochastic evolution of technology. The model has an infinite-horizon, overlapping generations structure in which young agents make human capital investments that are specific to the current cutting-edge technology, while old workers do not reinvest.[2] As technology evolves, although experience may allow the old to become more physically productive, the value of the human capital of older workers is eroded—to varying degrees depending on the extent of improvements in technology—by competition from young workers whose skills are tailored to the newest technology. We characterize equilibrium entry of young workers, especially the degree to which advances in technology generate entry. In Section IV we show that certain industry characteristics—among them inelastic product demand,

[1] There are obvious exceptions to this statement: the "superstar" architects whose buildings and faces appear in trade journals and the popular press. We discuss the superstars phenomenon below.

[2] Zeckhauser (1968) and Parente (1994) have studied optimal skill updating when there is learning by doing given use of a particular technology, but technology is steadily improving (see also Greenwood and Jovanovic 2001). Laing, Palivos, and Wang (2003) consider a general equilibrium search model in which intergenerational competition akin to the competition we emphasize has implications for the macroeconomy, e.g., unemployment, growth, and income distribution.

persistent technology change, and weak experience effects or consumers' finding the old's output less substitutable for the young's—tend to cause entry by the young to decline in response to advancing technology.

Especially when experience effects are weak relative to the impact of new technology, reduced entry can lead to a feature—which we refer to as the "has-beens" effect—similar to one that is well known to students of industry life cycles and suggestive of the architecture example. In the industry life cycle case, new technology leads to a smaller number of large-scale producers, with the less efficient being driven out (see Gort and Klepper 1982; Jovanovic and MacDonald 1994). In our model, the less efficient are older workers whose sunk investments lead them to continue to work. Technological advance results in a comparatively small number of young, highly productive, workers, whose entry increases output and reduces the value of older workers' output. When this occurs, advances in technology can cause the within-industry distribution of income between young and old to become right-skewed in that a smaller number of younger workers each earn more than each old worker. The old are especially affected when technology evolves rapidly since they are comparatively more numerous, earn comparatively less, and are absolutely worse off in that the price of their output is lower.

The has-been phenomenon is different from Rosen's (1981) superstars idea but has clear similarities. Superstars earn relatively more as a result of superior talent and the way talent interacts with other choices. There is free entry to being ordinary, and superior ability commands a rent. In the dynamic, rising stars, version, the young enter hoping that as time passes events will reveal superior talent and that superstardom will follow (see MacDonald 1988). In the has-beens phenomenon, there is free entry to use of advanced technology, and within-industry differences in relative output or compensation reflect the interaction of experience adding to the skills of older workers with deterioration in their rents as technology advances and intergenerational competition lowers the value of what the old can produce. (Cooley, Greenwood, and Yorukoglu [1997] and Campbell [1998] emphasize this economic, as opposed to purely physical, depreciation, but as applied to physical capital.) The young enter hoping that technology will evolve in a way that depreciates their skills minimally as they age.

In the sections following, we set out the model, define an equilibrium, and discuss our results. Then we discuss some extensions, limitations, and related ideas; for example, the model suggests a novel explanation for academic tenure.[3]

[3] Some of the technical aspects of our analysis are carried out by reformulating the problem as an infinite-horizon stochastic dynamic programming problem. This reformulation appears in the Appendix.

II. Model

Time, t, is discrete, and the horizon is infinite, $t = 0, 1, \ldots$. At each t, a unit mass of agents is born and lives for two periods. Thus there is a continuum of "young" (y) and "old" (o) agents at every date beyond $t = 0$. All agents are risk-neutral expected wealth maximizers who inelastically supply a fixed amount of time to work each period. Denote their common discount factor by β, where $0 < \beta < 1$. To focus on the impact of accumulation of technology-specific capital, we assume that agents are born identical.

We study an industry (defined by the homogeneous, nonstorable product firms produce) that is small in relation to the rest of the economy. The impact of the small-industry assumption is that the evolution of the rest of the economy is independent of the way technology evolves in the industry.

Demand for the industry's product is stationary and depends on the current price of the product, p, and aggregate income, Y; the numeraire is the composite good produced elsewhere in the economy. Inverse demand is $p = D(Y, Q)$, where Q is quantity, and D is a positive, bounded, continuous, and increasing function of Y/Q, that is,

$$p = D\left(\frac{Y}{Q}\right). \tag{1}$$

Agents decide whether to work in the industry or in the rest of the economy. Whichever is chosen, every agent, when young, must make a technology-specific human capital investment. This capital may be put to work immediately, and old agents do not reinvest. Also, human capital is useless unless employed in conjunction with the associated technology, and there is no other human capital. Direct investment costs are ignored: investment costs are all opportunity costs. The impact of these assumptions is that old agents will do what they did when they were young.

To allow for experience-related growth in human capital or age-related depreciation, we assume that agents' productivity when old is γ times their productivity when young.[4] Note that γ reflects physical accumulation or depreciation in the skills of older workers, not the revaluation of human capital that we focus on below. In many applications, $\gamma > 1$ appears most descriptive since more experienced workers have found more efficient ways to produce output. But in others, where physical prowess or enthusiasm is more critical, workers may be less productive as they age, $\gamma < 1$. We allow either and simply assume $\gamma \geq$

[4] Implicitly, γ is the same in the industry and the rest of the economy. This restriction is easily relaxed.

0. Further, while we shall interpret γ in terms of an experience effect, note that it can also parameterize the degree to which consumers view the young's output as better than or less substitutable for (both have $\gamma < 1$) the old's output.

The technology-specific investment can be given a broad interpretation. For example, while it is convenient to refer to it as human capital, the model can also be interpreted in terms of physical or even organizational capital in the sense of an industry practice or corporate culture, and so forth. The key is that when the agent has made the investment, it will be in place and in use for a period of time likely to exceed that for which the current technology is the cutting edge.

Having made a technology-specific investment, the agent can put it to use. Production is modeled as an individual activity, although, as usual, it can be interpreted as the outcome of constant returns to scale production. For now, other factors of production are ignored (but see Sec. V*B*).

Let individual productivity in the rest of the economy be q_a. Since our objective is to understand the role of advancing technology in the industry, to study this while assuming that the industry remains small in comparison to the economy, the rest of the economy must grow. Thus we assume that q_a improves by the factor δ every period, where $\delta > 1$ and $\beta\delta < 1$. Thus, since we denote future values of variables with a prime, $q'_a = \delta q_a$.

A young agent who elects to produce in the industry invests in the best practice technology and puts it to use for two periods (with productivity rising with experience by the factor γ). Let $\tilde{q}_y$ denote the productivity of the technology when learned. Since agents who are young in the current period will be old in the next, the productivity of old agents in the industry next period, q'_o, is the current period's best practice productivity, with allowance for experience, $q'_o = \gamma\tilde{q}_y$.

The idea that the evolution of technology in the industry is both hard to predict and to some degree distinct from the evolution of technology in the rest of the economy plays a central role in the model. We assume that $\tilde{q}'_y$ has density $\tilde{\varphi}(\cdot|\tilde{q}_y, q_a)$, satisfying $\Pr(\tilde{q}'_y \leq \tilde{q}_y|\tilde{q}_y, q_a) = 0$.

III. Analysis

A. Agent Optimization

Young agents must decide whether to enter the industry or to participate in the rest of the economy. This decision hinges on a comparison of expected discounted incomes. The state variables determining the value of entry or participation in the rest of the economy are (i) the productive opportunities in the industry and elsewhere, $\tilde{q}_y$ and q_a, since they determine the quantities the worker might produce and how productivity in the industry evolves, via $\tilde{\varphi}$; and (ii) the productivity and mass of old workers in the industry, q_o and o, since they play a role in determining the price of the industry's product (recall that the price of output produced elsewhere is the numeraire). Specifically, since price is influenced by the total output of old workers, $q_o o$, we define the *installed base* of older human capital to be $\tilde{b} \equiv oq_o$.

To proceed, define the state vector $\tilde{\mathbf{s}} \equiv (\tilde{q}_y, q_a, \tilde{b})$, and for any $\tilde{\mathbf{s}}$, let $P(\tilde{\mathbf{s}})$ be the prevailing product price and $e(\tilde{\mathbf{s}})$ the mass of young entrants. The functions P and e will be determined in equilibrium; each agent takes P and e as given.

Consider a young worker's decision problem given some $\tilde{\mathbf{s}}$. By entering the industry, the worker earns $P(\tilde{\mathbf{s}})q_y$ in the current period and $P(\tilde{\mathbf{s}}')\gamma q_y$ in the next. Thus expected discounted income for a young worker entering the industry is

$$\tilde{q}_y\left[P(\tilde{\mathbf{s}}) + \beta \int \gamma P(\tilde{\mathbf{s}}')\tilde{\varphi}(\tilde{q}_y' | \tilde{q}_y, q_a) d\tilde{q}_y'\right], \tag{2}$$

where $\tilde{q}_y' \sim \tilde{\varphi}(\cdot | \tilde{q}_y, q_a)$, $q_a' = \delta q_a$, and, since current entrants are the future old generation, $\tilde{b}' \equiv o'q_o' = e(\tilde{q}_y, q_a, \tilde{b})\gamma\tilde{q}_y$. In contrast, work in the rest of the economy yields q_a in the current period and γq_a in the next, with discounted value[5]

$$q_a(1 + \beta\gamma). \tag{3}$$

The worker will simply make the human capital investment yielding the larger of (2) and (3).

B. *Equilibrium*

Since all young workers are identical, equilibrium determines the mass of young agents entering the industry, but not the identities of the entering workers. This is analogous to the familiar perfectly competitive model of homogeneous firms in which entry must suffice to ensure zero profit for entering firms, but entry by any set of firms yielding this outcome is consistent with equilibrium. Thus equilibrium is defined in terms of the mass of entrants in any state. Also, the equilibrium price

[5] We assume that a young agent operating in the rest of the economy earns q_a when young and γq_a when old, as opposed to earning $\gamma\delta q_a$ when old. The interpretation of this specification is that productivity growth is the result of technological advance learned by the young, as opposed to the accumulation of other capital inputs that would be available to young and old. The opposite assumption can be made with obvious modifications to the analysis.

must equate supply and demand for the industry's product. Formally, an *equilibrium* is a pair of functions, $(e(\cdot), P(\cdot))$ such that, for all $\tilde{\mathbf{s}}$,

$$\tilde{q}_y\left[P(\tilde{\mathbf{s}}) + \beta\gamma \int P(\tilde{\mathbf{s}}')\tilde{\varphi}(\tilde{q}'_y \mid \tilde{q}_y, q_a)d\tilde{q}'_y\right]\begin{cases} = q_a(1+\beta\gamma) & \text{if } e(\tilde{\mathbf{s}}) > 0 \\ \leq q_a(1+\beta\gamma) & \text{if } e(\tilde{\mathbf{s}}) = 0 \end{cases} \quad (4)$$

and

$$P(\tilde{\mathbf{s}}) = D\left(\frac{q_a[1+(\gamma/\delta)]}{\tilde{b} + e(\tilde{\mathbf{s}})\tilde{q}_y}\right), \quad (5)$$

where $\tilde{\mathbf{s}}' \equiv (\tilde{q}'_y, q'_a, \tilde{b}') = (\tilde{q}'_y, \delta q_a, e(\tilde{q}_y, q_a, \tilde{b})\gamma\tilde{q}_y)$.

According to (4), if a positive mass of agents enter the industry, equilibrium requires that their expected discounted lifetime income equal the value they could achieve elsewhere in the economy. Likewise, if there is no entry, expected discounted lifetime income must be no greater than the value an agent could achieve elsewhere.[6] Equation (5) stipulates that the product market clear in each state. Since the industry is assumed small relative to the economy as a whole, aggregate income is simply income earned by the unit mass of young workers elsewhere in the economy, q_a, together with income earned elsewhere by the unit mass of old workers who learned a less productive technology when young but who have also had the benefit of experience, $q_a(\gamma/\delta)$. Finally, industry output is $Q = \tilde{b} + e(\tilde{\mathbf{s}})\tilde{q}_y$. Equation (5) is simply (1) with these substitutions.

C. Some Simplification

There are two features of the economic environment that are critical when the young consider investing in industry-specific human capital. Adding a little extra structure allows the central, and intuitive, role these elements play to be highlighted. The first element is the physical productivity of industry-specific capital compared to physical productivity in the rest of the economy, that is, $\tilde{q}_y$ versus q_a. This comparison matters since it plays a key role in determining both the young's current income and the probability distribution of future income. The second is how "crowded" the industry is, specifically, the size of the installed base of older human capital, $\tilde{b}$. The installed base is important since it influences the price at which the industry's output can be sold and therefore,

[6] Consistent with our assumption that the industry is small in comparison to the rest of the economy, we assume that there are enough young workers to allow (4) to be met with equality in any state for which $e(\tilde{\mathbf{s}}) > 0$.

together with $\tilde{q}_y$, affects the income accruing to any young entrant. To highlight the roles of $\tilde{q}_y$ versus q_a and $\tilde{b}$, notice that (5) can be written

$$P(\tilde{\mathbf{s}}) = D\left(\frac{1 + (\gamma/\delta)}{(\tilde{b}/q_a) + e(\tilde{\mathbf{s}})(\tilde{q}_y/q_a)}\right). \tag{6}$$

For price determination, what matters is not the state vector $(\tilde{q}_y, q_a, \tilde{b})$, but simply $(\tilde{q}_y/q_a, \tilde{b}/q_a)$, that is, individual productivity in the industry relative to productivity in the rest of the economy, and the installed base, also measured relative to individual productivity elsewhere. Further, (4) can be written

$$\frac{\tilde{q}_y}{q_a}\left[P(\tilde{\mathbf{s}}) + \beta\gamma \int P(\tilde{\mathbf{s}}')\tilde{\varphi}(\tilde{q}_y'|\, \tilde{q}_y, q_a)d\tilde{q}_y'\right]\begin{cases} = 1 + \beta\gamma & \text{if } e(\tilde{\mathbf{s}}) > 0 \\ \leq 1 + \beta\gamma & \text{if } e(\tilde{\mathbf{s}}) = 0. \end{cases} \tag{7}$$

Given (6), the solution to (7), the entry function $e(\tilde{\mathbf{s}})$, depends only on $(\tilde{q}_y/q_a, \tilde{b}/q_a)$ if the distribution of q_y'/q_a', which we shall denote $\varphi(\cdot|\, \tilde{q}_y, q_a)$, can be written as $\varphi(\cdot|\, \tilde{q}_y/q_a)$. Since the analysis to follow is simplified considerably, we assume that φ has this structure.[7] With this assumption, the key features of the environment that determine the relative attractiveness of the human capital investments available to the young are simply the physical productivity of the industry-specific human capital relative to productivity elsewhere,

$$q_y \equiv \frac{\tilde{q}_y}{q_a}, \tag{8}$$

and the installed base relative to individual productivity elsewhere,

$$b \equiv \frac{\tilde{b}}{q_a}. \tag{9}$$

Equations (4) and (5) can be simplified to, for all (q_y, b),

$$q_y\left[P(q_y, b) + \beta\gamma \int P(q_y', b')\varphi(q_y'|q_y)dq_y'\right]\begin{cases} = 1 + \beta\gamma & \text{if } e(q_y, b) > 0 \\ \leq 1 + \beta\gamma & \text{if } e(q_y, b) = 0, \end{cases} \tag{10}$$

[7] An example of a distribution, φ, satisfying this property is as follows. Suppose that $\tilde{q}_y'$ evolves according to

$$\tilde{q}_y' = X\max\{\tilde{q}_y, q_a\},$$

where X is a random variable with support $[1, \bar{x}]$, $\bar{x} < \infty$. Then, when we divide by δq_a and recall that $q_a' = \delta q_a$, $\tilde{q}_y'/q_a'$ evolves according to

$$\frac{\tilde{q}_y'}{q_a'} = \frac{X}{\delta}\max\left\{\frac{\tilde{q}_y}{q_a}, 1\right\}.$$

where $e(q_y, b)$ is entry in state (q_y, b), q'_y is determined by $\varphi(\cdot|q_y)$, and $b' = e(q_y, b)q_y(\gamma/\delta)$. Then current and future prices are given by

$$P(q_y, b) = D\left(\frac{1 + (\gamma/\delta)}{b + e(q_y, b)q_y}\right) \tag{11}$$

and

$$P(q'_y, b') = D\left(\frac{1 + (\gamma/\delta)}{e(q_y, b)q_y(\gamma/\delta) + e[q'_y, e(q_y, b)q_y(\gamma/\delta)]q'_y}\right). \tag{12}$$

IV. Results

In this section we explore how advances in technology influence entry; how this affects older workers, the has-beens, whose skills are revalued when technology advances; and its consequences for relative income of young and old in an industry.[8]

A. *How Does Entry Respond to Technology's Advance?*

A young worker's entry decision involves a comparison of the expected present value of income from entry, the left-hand side of (10), versus the present value of income from work elsewhere. Specifically, the expected present value of income from entry is the product of the quantity of human capital a young agent acquires by entering, q_y, and

$$P(q_y, b) + \beta\gamma \int P(q'_y, b')\varphi(q'_y|q_y)dq'_y,$$

which, for brevity, we shall refer to as the *full price of human capital.*

When technology in the industry improves, that is, q_y increases, the young's return to entry is affected through several channels. The equilibrium level of entry by young workers adjusts until the return from entering the industry again equals the return from working outside the

[8] Since the economy we study is competitive, equilibrium human capital investment is efficient and coincides with the solution to a planner's dynamic programming problem in which the planner selects entry to maximize social surplus (see the Appendix). This more notation-intensive approach yields two facts we employ below. First, the planner's value function is concave in *b;* this follows from the fact that inverse demand is increasing in Y/Q. The second fact is the second-order condition for the planner's optimal choice of entry in those states for which entry is strictly positive. This condition is equivalent to the left-hand side of (10), the lifetime returns to entry by a young agent, being declining in the number of young agents entering the industry. Given this second-order condition, the signs of the derivatives of $e(q_y, b)$ are the same as the signs of the partial derivatives of the left-hand side of (7), with substitution of (11) and (12). Throughout this section and the next, the discussion focuses on states for which $e(q_y, b) > 0$.

industry. Thus we begin by considering how technology affects the lifetime income a young entrant expects, for a given level of current entry.[9]

An increase in q_y influences the value of entry in three ways. The first is quite direct. That is, from the left-hand side of (10), given the full price of human capital, an increase in q_y increases the value of entry proportionally, making entry more attractive. Thus, in the absence of some response through the full price of human capital, the young would find entry strictly preferable to work in the rest of the economy.

There are two channels through which technology, q_y, influences the value of entry through its effects on the full price of human capital. First, an increase in q_y makes entrants more productive when they are young. This works to lower the current product price (see eq. [11]). Further, together with any impact of experience on skills (γ), an increase in q_y means that young entrants will also be more productive when they are old, so increased q_y leads to a larger future installed base. This also tends to lower the future product price; see the first term in the denominator of the right-hand side of (12). But when the future installed base rises, this also influences future entry; see the second term in the denominator of the right-hand side of (12). And it is easy to show that whenever the installed base rises, concurrent entry falls. Thus reduced future entry alleviates some of the downward pressure on the future price created by an increase in q_y. However, some algebra reveals that the net impact of these two effects on the price expected in the future must be to reduce it; that is, whatever the magnitude of the effect of greater q_y on future entry is, it cannot be large enough to offset the downward pressure on future price implied by the greater future installed base. Thus, when current technology improves, given the level of current entry, there is downward pressure on both components of the full price of human capital, the current price as well as the future price. This tends to reduce the full price of human capital.

The final avenue through which improved technology influences the full price of human capital is the expectations about how technology will evolve in the future; that is, $\varphi(\cdot|q_y)$ depends on q_y. This matters for current entry because future technology will influence both the level of future entry and the productivity of each future entrant and thus the future product price, which is one key component of the full price of human capital. It is not clear what ought to be assumed about the way current technology influences expectations about future technology. For

[9] Since our measure of the young's productivity, q_y, is normalized by productivity elsewhere, when technology in the industry evolves more slowly than technology in the rest of the economy, as it might, e.g., for more mature industries, q_y falls. (Note, however, that *apart from the impact of experience*, the young have access to better technology than the old and are more productive.) In this case the results can be reinterpreted in the obvious way.

the moment we leave this effect unspecified, along with its impact on the attractiveness of the industry.

Altogether, *for a given level of current entry*, improved technology leads, given the full price of human capital, to a direct increase in the life income of the young, making the industry more attractive to them. But given expectations about the way the future technology will evolve, better technology also decreases *both* the current price of output and the price expected in the future, working to make the industry less attractive. Finally, better technology changes expectations about future technology, which also influences how the young view entry, since future technology determines their future income. The way that entry must adjust to maintain the relative attractiveness of the industry is a combination of these three effects.

With some calculations, the way all this combines to determine the overall response of entry to better technology can be fleshed out in an intuitive manner.[10] Refer to (11), which describes current price as a function of the current ratio of aggregate income to industry output, Q. Let η_Q^P be the elasticity of current price with respect to Q, that is, the elasticity of *inverse* product demand. Since inverse demand is downward sloping in Q, $\eta_Q^P < 0$. Next, let $\eta_{q_y}^Q$ be the elasticity of Q with respect to q_y, $0 < \eta_{q_y}^Q < 1$. In a similar manner, let $\eta_{Q'}^{P'}$ be (for given q_y') the elasticity of future price with respect to Q', and (also for given q_y') let $\eta_{q_y}^{Q'}$ be the elasticity of Q' with respect to q_y, $\eta_{Q'}^{P'} < 0$ and (with some calculation) $0 < \eta_{q_y}^{Q'} < 1$. Further, let σ represent the share of current price in the full price of human capital, that is,

$$\sigma \equiv \frac{P(q_y,\ b)}{P(q_y,\ b) + \beta\gamma\int P(q_y',\ b')\varphi(q_y'|q_y)dq_y'},$$

and σ' be the share of future price in the full price of human capital, that is,

$$\sigma' \equiv \frac{\beta\gamma P(q_y',\ b')}{P(q_y,\ b) + \beta\gamma\int P(q_y',\ b')\varphi(q_y'|q_y)dq_y'}.$$

Finally, for each q_y', let $\eta_{q_y}^{\varphi}$ be the elasticity of $\varphi(q_y'|q_y)$ with respect to q_y.[11]

With this notation in hand, a little algebra shows that the elasticity

[10] The elasticities defined in this paragraph, which will be reemployed later, all pertain to a *given* level of current entry.

[11] For simplicity we assume that the support of φ does not depend on q_y. In this case,

$$E(\eta_{q_y}^{\varphi}|q_y) \equiv \int \eta_{q_y}^{\varphi}\varphi(q_y'|q_y)dq_y' = 0.$$

of equilibrium entry with respect to improved technology, $\eta^{e}_{q_y}$, can be written

$$\eta^{e}_{q_y} = -1 + \frac{1 + E(\eta^{\varphi}_{q_y}\sigma'|q_y)}{-\eta^{P}_{Q}\eta^{Q}_{q_y}\sigma - E(\eta^{P'}_{Q'}\eta^{Q'}_{q_y}\sigma'|q_y)}, \tag{13}$$

where the expectation is taken with respect to the distribution of future technology, $\varphi(\cdot|q_y)$. Equation (13) can be interpreted as follows. First, suppose that future technological improvements do not depend on current technology; then $E(\eta^{\varphi}_{q_y}\sigma'|q_y) = 0$. Since the price elasticities are negative, (13) implies $\eta^{e}_{q_y} > -1$. The idea is straightforward. Suppose $\eta^{e}_{q_y} = -1$ ($\eta^{e}_{q_y} < -1$ follows easily). Then, when technology advances, entry adjusts in an exactly offsetting manner, and both the *total* output of current entrants and the future installed base do not change. Thus both the current product price and (since we have temporarily suppressed any impact of technology on expectations about future technology) the future price do not change either, leaving the full price of human capital unchanged. But as a result, all potential entrants would prefer entry to work elsewhere. Thus equilibrium entry cannot be so sensitive to new technology, that is, $\eta^{e}_{q_y} > -1$. The only caveat is the possibility that current technological improvements may alter expectations about future advances in a way that greatly suppresses current entry. We return to this possibility below. For now, we allow that technology advance may influence expectations about future advances, that is, $E(\eta^{\varphi}_{q_y}\sigma'|q_y) \neq 0$, but restrict attention to the most plausible case, in which $1 + E(\eta^{\varphi}_{q_y}\sigma'|q_y) > 0$; that is, the fraction on the right-hand side of (13) is positive. (The other case mirrors this one straightforwardly.) In this case, when technology improves, $\eta^{e}_{q_y} > -1$, and equilibrium entry must result in an increase in both the total output of the young and the future installed base, and downward pressure on current and future prices.

The term $-\eta^{P}_{Q}\eta^{Q}_{q_y}\sigma$ in the denominator of the ratio in (13) shows how improved technology translates into a lowered *current* product price and a corresponding impact on the full price of human capital. The magnitude of this term will vary from application to application in intuitive ways. Consider, for example, $-\eta^{P}_{Q}$. When demand for the industry's product is less elastic, inverse demand is more (negatively) elastic, and current price declines more in response to an improvement in technology. Thus, in industries displaying inelastic demand, when technology advances, achieving the equilibrium increase in the total output of the young may well require less entry than would have occurred had technology advanced more slowly, that is, $\eta^{e}_{q_y} < 0$. Thus industries in which demand is sufficiently inelastic will see fewer young enter when technology advances more quickly. Moreover, we have interpreted demand as demand for a final product; this is not necessary. The industry's product could be an input to home production, or a service or intermediate product whose demanders are firms. Under these assumptions, familiar reasoning about the elasticity of derived demand describes situations in which the elasticity of demand is likely to be small, that is, small elasticity of demand for the final product, low elasticity of substitution between the input and others, and so forth (see, e.g., Ferguson 1969, chap. 6).

Returning to the architecture example, note that demand for architects' services comes almost exclusively from residential or commercial construction, which are familiar examples of inelastic demand products. Furthermore, the elasticity of substitution between design inputs and material inputs is plausibly thought of as small. Thus the elasticity of derived demand for architectural services is small and the elasticity of inverse demand large. According to the model, then, if the older architects do not readily acquire the same skills as the young, the rapid advances in computing should have allowed comparatively few younger architects to take over much of the market for architectural services, while (because of free entry) earning only the lifetime income of those of comparable intelligence and motivation, but causing the older generation to lose much of its income.[12]

The rest of the term $-\eta_Q^P \eta_{q_y}^Q \sigma$ offers other insights. The factor $\eta_{q_y}^Q$ describes how changing the skills of the young alters (proportionally) current output in the industry. This varies with the share of the installed base, versus the young's output, in the industry's current output. If the industry is crowded with older workers, an improvement in the technology employed by any given number of young entrants yields a smaller proportionate effect on industry output. Thus, for a given elasticity of demand, technology improvement results in a smaller price response, and it is more likely that entry will respond positively. Likewise, if consumers see the old's output as worse than or less substitutable for the young's (i.e., γ is lower), this amounts to a reduction in the installed base, with the corresponding tendency for entry to respond negatively to new technology. Finally, the factor σ describes how important both current price and current income are in the full price of human capital and life income calculations. Suppose, for example, that the industry in question is one in which human capital (in physical units) grows little with age; that is, γ is low or even less than unity. In this case, current income is a particularly important component of life income, and so the impact of technology improvement on entry, operating through current-period price effects, is especially important.

[12] Similar comments apply to the economics profession, in which the demand for economists' services is derived from the demand for education, and technology change is the outcome of advances in basic research.

The term $E(\eta^{P'}_{Q'}\eta^{Q'}_{q_y}\sigma'|q_y)$ in the denominator of the ratio in (13) shows how improved technology translates into a lowered product price in the future and can be interpreted in much the same way that the second term was interpreted. There are two minor differences. First, an improvement in technology today puts downward pressure on price, and current entry is the only entity that can respond to this. But the same improvement also puts pressure on the future price, which, being anticipated, can be accommodated by both a change in current entry and a change in future entry. Since future entry declines when current entry increases, the impact of improved current technology on future output has a tendency to be somewhat muted in comparison to its impact on current output. The other difference is that the impact of improved technology, working through future price changes, can be either augmented or diminished, depending on the extent of experience-related human capital accumulation, that is, γ.

We now return to the numerator of the ratio in (13), $E(\eta^{\varphi}_{q_y}\sigma'|q_y)$. This expression captures the impact of improvements in current technology on the way future technology evolves and the manner in which this alters the full price of human capital and the entry decision of those who are currently young. In general, this term can take on either sign. There are two broad cases of interest, depending on the nature of the persistence in technology change. When current technology advance foreshadows even greater future advance, this augments the downward pressure on the future price that increases in q_y create, working to reduce current entry, that is, $\eta^{e}_{q_y} < 0$. Intuitively, the young appreciate that technology is likely to continue to advance and so cause industry output to be high in the future, resulting in a low future product price and low future income for them; this tends to reduce current entry, that is, $E(\eta^{\varphi}_{q_y}\sigma'|q_y) < 0$.[13] Likewise, when significant advances tend not to be repeated, the young anticipate that technology is unlikely to have advanced further when they are old. Thus they anticipate comparatively high future prices, which tends to increase current entry, that is, $E(\eta^{\varphi}_{q_y}\sigma'|q_y) > 0$. This suggests that in applications in which new technology "stands on the shoulders" of previous versions, better technology is likely to engender comparatively less entry simply because the industry is likely to become crowded as even better technology emerges. The effect is the opposite for applications in which technology is negatively persistent; that is, current advances suggest that future improvements are going to be hard to achieve. The case we emphasize, $E(\eta^{\varphi}_{q_y}\sigma'|q_y) > -1$, allows that technology might be positively persistent, but not so persistent that, in equilibrium, better technology today leads to entry that is

[13] Rosenberg (1976) discusses a similar idea, but applied to the firm's decision to adopt new technology.

so low that the young's total output is lower, and price higher, than it would have been had technology advanced more slowly.

B. How Does Technology Advance Influence Older Workers' Income?

An older worker's income is $P(q_y, b)q_o$, where q_o is the human capital accumulated when young, scaled by the impact of experience, γ. Thus the only avenue through which current technology can influence an older worker's income is the current price of the product. Using the elasticity expressions defined earlier, we can write the elasticity of current price with respect to technology improvement, $\eta^P_{q_y}$, as

$$\eta^P_{q_y} = \eta^P_Q \eta^Q_{q_y}(1 + \eta^e_{q_y}),$$

or, with (13),

$$\eta^P_{q_y} = \eta^P_Q \eta^Q_{q_y} \frac{1 + E(\eta^\varphi_{q_y}\sigma' | q_y)}{-\eta^P_Q \eta^Q_{q_y}\sigma - E(\eta^{P'}_{Q'}\eta^{Q'}_{q_y}\sigma' | q_y)}, \qquad (14)$$

which is negative in the case we emphasize, that is, $1 + E(\eta^\varphi_{q_y}\sigma' | q_y) > 0$. To get some intuition, begin by assuming that current technology does not affect the way future technology evolves, that is, $E(\eta^\varphi_{q_y}\sigma' | q_y) = 0$. When technology evolves, the full price of human capital adjusts so that the young are indifferent about entry. As discussed above, the change in the full price of human capital is a blend of changes in the current and future prices. Thus the impact of a given technology change on the old depends on how importantly adjustments to the current price figure in changes in the full price. For example, suppose that the industry is a mathematics-like, creative, endeavor in which older workers produce little; that is, γ is relatively small and σ large. In anticipation of this, when technology advances, changes in the current price are the primary vehicle though which the full price adjusts. In this instance, comparatively rapid technological advance results in comparatively large current price changes, with correspondingly large effects on the value of old workers' output. When $E(\eta^\varphi_{q_y}\sigma' | q_y) \neq 0$ is allowed for, as discussed earlier, and technological change is persistent, better current technology tends to suppress current entry. Thus, by a reduction in the numerator of (14), technology advance has a less dramatic effect on the old.

C. Young/Old Relative Income Distribution

Since the young and old have different physical productivities, there is (unless the impact of experience happens exactly to offset the improvement in technology) a nondegenerate distribution of income in the industry. That is, the proportion $e/(e + o)$ earn (measured in terms of the income of the older workers) q_y/q_o, and the balance, $o/(e+o)$, earn one.[14] The speed of technology's evolution thus has implications for the distribution of relative income and influences the degree to which the old become relative has-beens.

Since the human capital of older workers is fixed at the time young workers enter, the relative income of young and old, and so the *support* of the distribution of relative income, depends only on the extent to which technology evolves; that is, the higher q_y is, the higher q_y/q_o is. In this sense, the old are always has-beens to some degree, and the size of the has-been effect increases with the size of the technology advance. But the impact of better technology on the distribution of relative income also depends on how the proportion earning each income evolves in response to technology change. That is, $e/(e+o)$ increases or decreases with different degrees of technology advance depending on whether $\eta^e_{q_y}$ is positive or negative. Altogether, changes in q_y, together with $\eta^e_{q_y}$, determine the extent to which the industry is dominated by relatively few high-output, young workers or whether the old remain relatively few in number and have a relatively high income.

The discussion of (13) in subsection *A* identified numerous industry characteristics that tend to cause entry to fall in response to technological advance, that is, negative $\eta^e_{q_y}$. For this discussion, we shall lump these features together and refer to industries displaying $\eta^e_{q_y} < 0$ as *inelastic* (vs. *elastic*) *product demand* industries. Next, whether increasing technology causes the young to close or expand the gap between their income and the income of the old depends on whether the young "typically" earn less or more than the old, that is, whether q_y/q_o is typically less than or greater than one. Since young workers' skills, being based on new technology, are always superior to the skills the old had when they were young, whether the young typically earn more or less than the old depends only on how much more productive the old become with experience, that is, the magnitude of γ. We shall refer to industries that typically display $q_y/q_o < 1$ as *experience-dominated*, and the rest as *technology-dominated*.

While the old are always has-beens to some extent, the relative income distribution implications of advancing technology show that there are industries in which there is a sense, distinct from the level effects discussed in subsection *B*, in which the has-beens effect is more significant in some industries than in others. Consider, first, an experience-dominated industry with elastic demand. In this case, the old generally earn more than the young, and technology advance results in increased entry of young workers. Thus, when technology advances, the old become a

[14] Combining the results of subsection *A* with those in the present subsection, one can obtain implications for the distribution of income measured in units of the numeraire.

relatively smaller share of the income distribution, and the young close the income gap to some degree. Faster technology advance still leaves older workers in the comparatively comfortable position of being a relatively small group of more highly paid individuals. At the other extreme, in which the industry is technology-dominated and has inelastic demand, the young tend to earn more, and advancing technology reduces entry. In this case faster technology advance makes the young an even smaller group of even more relatively highly paid individuals. The other cases—that is, technology-dominated industries with elastic demand and experience-dominated industries with inelastic demand—are intermediate. Overall, inelastic demand and the relative importance of technology evolution in comparison to experience effects work to exaggerate the distributional impact of advancing technology.

V. Discussion

A. Output versus Income

The discussion in Section IV*C* identifies factors that influence the extent to which technological advance depreciates the skills of the older generation. While the model's results strictly concern output, they can also be stated in terms of income and thus have implications for the welfare of older workers.

However, there are reasons why the patterns predicted by our model may be difficult to detect empirically. First, to the extent that technological advance is anticipated and is out of the control of most participants, risk-averse agents will tend to adopt contractual arrangements that hedge the risks of technological advances (see Weinberg 2001). For example, academic tenure, together with the common practice of nonnegative salary increments, can be interpreted as a contractual design intended to bound the impact of potential new technologies on young workers. The young anticipate the protection they will enjoy when they are older should new developments depreciate their human capital. Second, incentive considerations when workers' efforts are imperfectly observed, especially in a dynamic setting, will generally lead worker pay and productivity to differ at each point in time, with pay typically lagging productivity for young workers (see Lazear 1979). When firms use these types of compensation arrangements, they will offset the effects discussed here to some extent.

B. Other Factors

In the model, young/old relative output and the relative productivity of their technologies are defined to be identical. But just as Rosen (1981) distinguishes between ability and other factors of production and explores how choices of other factors interact to exaggerate ability differences, we may distinguish technology and other factors and investigate how these factors influence the has-been effect.[15] Suppose, for example, that technology is characterized by a neutral production function parameter; for instance, individual output is qK^{α}, where q represents technology level (q_y or q_o as appropriate), K is a competitively supplied factor of production, and α is a parameter, $0 < \alpha < 1$. Then equilibrium relative output is given by $(q_y/q_o)^{1+[\alpha/(1-\alpha)]}$. Thus, since $1 + [\alpha/(1 - \alpha)] > 1$, when technology evolves more quickly, the presence of other factors exaggerates the impact on output and income. In other words, other factors cause potentially small differences in relative productivities potentially to have large differences in output and income.

In the architect example, the young's facility with advanced technology expands the use not just of computers, but also of other technology-based inputs such as personal digital assistants, Web pages, video-conferencing, and so on, expanding relative productivity more than would occur purely as a result of the use of a computer as a design tool.

C. *Retirement*

The assumption that older workers do not learn new technologies greatly simplifies the analysis and is arguably descriptive of many industries. A second implicit assumption we make is that older workers keep working, no matter how low their relative productivity.[16] For many occupations, such as architecture, the option to retire midcareer is unlikely to be attractive no matter how fast technology has evolved. In such cases the ideas discussed above are robust to the possibility of retirement. But for others, especially highly compensated occupations such as professional sports, the possibility of early retirement can alter our results in a manner similar to the one that alters some superstars propositions. For example, in the superstars model, a rightward shift in the ability distribution increases skewness if there is no exit but may lead to a skewness-reducing thinning of the left tail when exit is allowed for. And in the has-beens model, even in technology-dominated industries with inelastic demand, the tendency for an increase in the pace of technology change to exaggerate the has-beens effect can be offset by the exiting of the old.

[15] Jovanovic (1998) studies a model in which there is a limited supply of the most up-to-date physical capital. When new technology and worker ability are complementary, the limited supply of leading-edge capital adds to the ability-induced inequality.

[16] Bartel and Sicherman (1993) find some empirical evidence consistent with more rapid technology change inducing retirement.

VI. Conclusion

Technological innovation has had a substantial impact on the productivity and welfare of many workers. Depending on the nature of technological evolution, the value of workers' human capital can be either enhanced or dissipated. The possibility that such technological advances may affect one's human capital affects workers' choice of occupation. This paper presents a model of this choice and derives its equilibrium implications.

If older workers do not have an inherent advantage when it comes to updating skills to take advantage of new technologies, technology's advance will tend to depreciate their skills, turning them into has-beens. The major channel through which this occurs is entry by younger workers, whose aggregate output exerts downward pressure on the price of what older workers produce. We identify the industry characteristics that augment or diminish the impact of technology on entry and the product price, and so either exacerbate or ameliorate the degree to which the old become has-beens. In particular, factors likely to be associated with a large has-beens effect are inelastic product demand, persistent technological change, weak experience effects, and consumers' finding the old's output less substitutable for the young's.

The analysis presented here suggests a number of directions for future research. First, the model is necessarily simplified and does not allow for some potentially important considerations. For example, workers cannot retool using new technologies or quit and find alternative occupations if theirs becomes sufficiently unattractive. In addition, a more flexible contracting environment in this setting could lead to equilibrium contracts designed to compensate for the has-been effect.

The model suggests numerous empirical questions that are worth pursuing. Does the sensitivity of wages to technology in fact vary with the elasticity of demand? What are the characteristics of experience-dominated and technology-dominated industries? But it also offers serious challenges for empirical analysis. How do we measure the extent to which technological uncertainty varies across industries? And as we emphasize above, observing the has-been effect is likely to be made difficult by contractual responses and by other incentive-related factors affecting age-earnings profiles.

Finally, the interaction of technology-specific capital and technology evolution is a much more general phenomenon than the one we study here. Similar ideas apply to investment in physical capital or acquisition of human capital inside organizations. For example, many companies have historically encouraged workers to develop firm-specific human capital by structuring workers' compensation so that they have incentives to remain with the organization. Thus steeply sloped age-earnings profiles, defined-benefit pension plans containing implicit penalties for changing jobs, and even promises of "lifetime" employment have been common at firms in which human capital is particularly important (see, e.g., Lazear 1995). A technological shift that makes obsolete the human capital of most of the workers leaves the firm with the unenviable choice of proceeding with the same workforce against competitors trained in the better technology, or laying off workers, breaking implicit promises to them, and living with the ensuing reputational damage. Eastman Kodak found itself in such a position in the early 1990s when the state of the art in the image-processing industry shifted from an analog approach to a digital one. And Xerox is facing the same challenges today as new approaches to reproduction, storage, and dissemination of documents were based on digital, instead of analog, technologies.

The way well-chosen contracts, human capital accumulation, and technology evolution interact is an important, and little understood, phenomenon. Our model provides one of the ingredients needed to begin analysis of this interaction.

Appendix

Dynamic Programming Representation

Given the state vector $\tilde{\mathbf{s}} \equiv (\tilde{q}_y, q_a, \tilde{b})$, the social planner's problem solves the dynamic program

$$\tilde{W}(\tilde{\mathbf{s}}) = \max_{e\geq 0}\left\{\int_0^{\tilde{b}+e\tilde{q}_y} D\left(\frac{q_a[1+(\gamma/\delta)]}{x}\right)dx - eq_a(1+\beta\gamma) + \beta\int \tilde{W}(\tilde{\mathbf{s}}')\tilde{\varphi}(\tilde{q}'_y|\tilde{q}_y, q_a)d\tilde{q}'_y\right\}.$$

With the change of variable $y \equiv x/q_a$ and recalling that $q'_a = \delta q_a$, we can write the Bellman equation as

$$\frac{\tilde{W}(\tilde{\mathbf{s}})}{q_a} = \max_{e\geq 0}\left\{\int_0^{(\tilde{b}/q_a)+e(\tilde{q}_y/q_a)} D\left(\frac{1+(\gamma/\delta)}{y}\right)dy - e(1+\beta\gamma) + \beta\delta\int \frac{\tilde{W}(\tilde{\mathbf{s}}')}{q'_a}\tilde{\varphi}(\tilde{q}'_y|\tilde{q}_y, q_a)d\tilde{q}'_y\right\}.$$

Defining $b \equiv \tilde{b}/q_a$ and $q_y \equiv \tilde{q}_y/q_a$ and invoking the assumption that the distribution of $q_y' \equiv \tilde{q}_y'/q_a'$ is conditioned only on q_y, we can write the Bellman equation as

$$W(q_y,\ b) = \max_{e\geq 0}\left\{\int_0^{b+eq_y} D\left(\frac{1+(\gamma/\delta)}{y}\right)dy - e(1+\beta\gamma) + \beta\delta\int W\left(q_y',\ \frac{e\gamma q_y}{\delta}\right)\varphi(q_y'|q_y)dq_y'\right\}, \tag{A1}$$

where

$$b' \equiv \frac{o'q_o'}{q_a'} = \frac{e\gamma\tilde{q}_y}{\delta q_a} = \frac{e\gamma q_y}{\delta}.$$

With some regularity conditions (see Stokey, Lucas, and Prescott 1989, theorems 9.8, 9.10), W is strictly concave and continuously differentiable in b.

When the optimal e is strictly positive, the first-order condition characterizing optimal entry is given by

$$q_y D\left(\frac{1+(\gamma/\delta)}{b+eq_y}\right) - (1+\beta\gamma) + \beta\gamma q_y\int W_2\left(q_y',\ \frac{e\gamma q_y}{\delta}\right)\varphi(q_y'|q_y)dq_y' = 0.$$

From (A1), for any $(q_y,\ b)$,

$$W_2(q_y,\ b) = D\left(\frac{1+(\gamma/\delta)}{b+eq_y}\right).$$

Then the first-order condition can be written

$$q_y\left[D\left(\frac{1+(\gamma/\delta)}{b+eq_y}\right) - (1+\beta\gamma) + \beta\gamma\int D\left(\frac{1+(\gamma/\delta)}{(e\gamma q_y/\delta)+e(q_y',\ e\gamma q_y/\delta)q_y'}\right)\varphi\,(q_y'|q_y)dq_y'\right] = 0,$$

that is, (10), with substitution from (11) and (12). The second-order condition is

$$D'\left(\frac{1+(\gamma/\delta)}{b+eq_y}\right)\cdot\frac{-q_y[1+(\gamma/\delta)]}{(b+eq_y)^2} + \beta\delta\int D'\left(\frac{1+(\gamma/\delta)}{(e\gamma q_y/\delta)+e(q_y',\ e\gamma q_y/\delta)q_y'}\right) \cdot\frac{-[1+(\gamma/\delta)]\left[(\gamma q_y/\delta)+q_y'\frac{\partial e(q_y',\ e\gamma q_y/\delta)}{\partial b}(\gamma q_y/\delta)\right]}{[(e\gamma q_y/\delta)+e(q_y',\ e\gamma q_y/\delta)q_y']^2}\varphi(q_y'|q_y)dq_y' \leq 0.$$

With some calculations, the concavity of W in b implies that both terms in the second-order condition are negative.

References

Bartel, Ann P., and Nachum Sicherman. 1993. "Technological Change and Retirement Decisions of Older Workers." *J. Labor Econ.* 11, no. 1, pt. 1 (January): 162–83.

Campbell, Jeffrey R. 1998. "Entry, Exit, Embodied Technology, and Business Cycles." *Rev. Econ. Dynamics* 1 (April): 371–408.

Cooley, Thomas F., Jeremy Greenwood, and Mehmet Yorukoglu. 1997. "The Replacement Problem." *J. Monetary Econ.* 40 (December): 457–99.

Ferguson, Charles E. 1969. *The Neoclassical Theory of Production and Distribution.* London: Cambridge Univ. Press.

Gort, Michael, and Steven Klepper 1982. "Time Paths in the Diffusion of Product Innovations." *Econ. J.* 92 (September): 630–53.

Greenwood, Jeremy, and Boyan Jovanovic. 2001. "Accounting for Growth." In *New Directions in Productivity Analysis,* edited by Charles R. Hulten, Edwin R. Dean, and Michael J. Harper. Chicago: Univ. Chicago Press (for NBER).

Jovanovic, Boyan. 1998. "Vintage Capital and Inequality." *Rev. Econ. Dynamics* 1 (April): 497–530.

Jovanovic, Boyan, and Glenn M. MacDonald. 1994. "The Life Cycle of a Competitive Industry." *J.P.E.* 102 (April): 322–47.

Laing, Derek, Theodore Palivos, and Ping Wang. 2003. "The Economics of 'New Blood.'" *J. Econ. Theory* 72 (September 2003): 106–56.

Lazear, Edward P. 1979. "Why Is There Mandatory Retirement?" *J.P.E.* 87 (December): 1261–84.

———. 1995. *Personnel Economics.* Cambridge, Mass.: MIT Press.

MacDonald, Glenn M. 1988. "The Economics of Rising Stars." *A.E.R.* 78 (March): 155–66.

Parente, Stephen L. 1994. "Technology Adoption, Learning-by-Doing, and Economic Growth." *J. Econ. Theory* 63 (August): 346–69.

Rosen, Sherwin. 1981. "The Economics of Superstars." *A.E.R.* 71 (December): 845–58.

Rosenberg, Nathan. 1976. "On Technological Expectations." *Econ. J.* 86 (September): 523–35.

Stokey, Nancy L., Robert E. Lucas, Jr., and Edward C. Prescott. 1989. *Recursive Methods in Economic Dynamics.* Cambridge, Mass.: Harvard Univ. Press.

Weinberg, Bruce A. 2001. "Long-Term Wage Fluctuations with Industry-Specific Human Capital." *J. Labor Econ.* 19 (January): 231–64.

Zeckhauser, Richard. 1968. "Optimality in a World of Progress and Learning." *Rev. Econ. Studies* 35 (July): 363–65.