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SELF-FULFILLING EXPECTATIONS AND ECONOMIC GROWTH: A MODEL OF TECHNOLOGY ADOPTION AND INDUSTRIALIZATION*

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In this work we construct a model that integrates both industrialization and endogenous growth. We feature the role of technology adoption in sustaining growth and achieving industrialization. Our economy contains multiple equilibria for an initial history. We found that only self-fulfilling expectations matter in selecting an equilibrium, whereas history plays no role. Our equilibrium is shown to involve a threshold property: when the economy starts above this threshold, the economy is able to sustain growth; otherwise, it is not. Both the rate of economic growth and the process of industrialization increase gradually and approach an upper bound.

1. INTRODUCTION

Models of industrialization developed by Murphy et al. (1989a, 1989b) and by Matsuyama (1991) and of endogenous growth pioneered by Romer (1986) and by Lucas (1988) have been the subject of increasing research interest.

The literature of industrialization underscores why an economy fails to industrialize and how this economy can industrialize.[2] By industrialization we mean the shift of resources from a traditional to a manufacturing and modern sector, or increased size of a modern sector. Among the works of industrialization, Murphy et al. (1989a, 1989b) used an intrinsically static model to study the conditions under which both a zero and a full level of industrialization coexist. Matsuyama's (1991) model was dynamic, but contained only steady states and equilibria leading to a steady state. No growth was involved in these models.

Models of endogenous growth are strongly concerned with economic growth.[3] In these models, a sustained economic growth rate not only is possible but is the result

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2 The investigation of industrialization is traced to the work of Rosenstein-Rodan (1943) and Nelson (1956).

3 For readers unfamiliar with this literature, consult, among others, Sala-i-Martin (1990) and Helpman (1992) for a survey.

of optimal choices of individuals. This result has implications for persistent income discrepancies among countries in the world. However, no relation between industrialization and economic growth was investigated.

In our work we attempt to integrate these two lines of research. In our view, in a process of industrialization a positive economic growth rate is in general sustained. Casual observation of the following indicates this condition. In the process of industrializing their economies, Japan in the early stage of development and four Asian tigers in the past two decades, for example, have achieved 'miraculous' growth rates (see Lucas 1993). Recently, several Asian countries such as China, Indonesia, Malaysia, the Philippines, and Thailand have endeavored to adopt foreign technologies to industrialize their countries. They provided inexpensive land, tax deduction and other benefits to attract technology and capital from Japan, Taiwan and other relatively developed countries. As a result, these countries achieved industrialization rapidly and shared the greatest rate of economic growth in the world.

For our purpose, we build a basic model that draws on Matsuyama (1991) to construct the structure of technologies and demography. We are thus able to study the process of industrialization. Our model differs from that of Matsuyama in that in our model an agent is permitted to switch to a potentially more productive industry after he is born if he wants to learn the skill for the switch, whereas every individual decides his sector of work at the beginning of his life, according to Matsuyama (1991). We also incorporate the learning-by-doing effect of Arrow (1962) and Lucas (1988). This effect serves as a source for the engine of economic growth. Specifically, when an individual learns a skill to shift to a potentially productive industry, a knowledge is generated as a by-product of this industry that results in learning-by-doing. For convenience this knowledge is called human capital. The decision to learn a skill leads to industrialization, and the knowledge or by-product of the learning leads to sustained economic growth because the knowledge accumulates over time.

More specifically, we assume the economy to consist of technology of two types, producing a homogenous product that uses only labor as input. One type, called traditional technology, possesses a constant labor productivity and is freely available. Another type, called modern technology, is not freely accessible and needs learning. The modern technology has a constant labor productivity at a point in time, but its productivity is affected by the stock of human capital in the economy. The stock of human capital increases during the process when agents learn to adopt modern technology and the unit labor productivity of modern technology increases in the stock of human capital. Hence, the productivity of modern technology is assumed to be subject to an industry-wide effect of learning-by-doing. The existence of external economies in manufacturing industry has been confirmed in empirical studies conducted both by Caballero and Lyons (1990, 1992) in four European countries and the U.S.A., and by Chan et al. (1995) in Taiwan. We believe a similar mechanism appears in modern manufacturing industry in most countries. Given technology of these two types, an entrepreneur with a traditional technology then decides whether to adopt a modern technology. As we noted above, his decision affects the industry-wide stock of human capital and thus affects the productivity of the technology. The stock of human capital is accordingly a byproduct of optimization of individuals.

With the above structure, our interest is in the following questions. First, is a positive economic growth rate sustainable, given the option of adopting modern technology and the externality resulted from the adoption of technology? We derive the condition under which a positive rate of growth is sustainable. We then ask, under the condition that a positive rate of growth is sustainable, how does the growth rate vary with time, and how does the process of industrialization look? We briefly provide the answer to the first question here, and leave the remainder to succeeding sections.

For a given initial history,[4] our economy contains multiple equilibria. The economic equilibrium is shown to involve a threshold property. When the expected excess income to adopt a modern technology exceeds a threshold, agents learn to adopt modern technology and the economy is therefore able to achieve a positive rate of growth in equilibrium regardless where the history starts; otherwise, the rate of economic growth becomes zero eventually. In our equilibrium, only expectations matter is selecting an equilibrium, whereas history plays no role. Both sustained economic growth and industrialization are generated at the same time, according to our model.

For literature related to our work, the distinction between history and expectations seems particularly important. This literature investigates in a framework with multiple steady states the relative importance of state variables (history) and self-fulfilling expectations in determining an equilibrium path leading to a particular steady state. For example, according to Ethier (1982), Panagariya (1986), and Krugman (1987), among others, history determines the eventual choice of an equilibrium; in Krugman (1991) and Matsuyama (1991), both history and expectations matter; whereas in Howitt and McAfee (1988), Diamond and Fudenberg (1989) and Murphy et al. (1989a), only expectations count. As in the last three studies, an equilibrium is selected based solely upon expectations as is ours, a comparison of their works is deserved. Both Howitt and McAfee (1989) and Diamond and Fudenberg (1989), however, studied unemployment and thus not industrialization; it is difficult to compare our work with theirs. Although Murphy et al. (1989a) studied industrialization, their model features the condition under which both a zero and a full level of industrialization coexist and the possibility of a big push to a full level of industrialization. As their model involves no dynamics, expectations help only to identify the coexistence of two steady states.

We must compare our work with that of Matsuyama (1991) as our model generates a distinct mechanism in selecting an equilibrium, although it draws on Matsuyama's work. As we mentioned above, the agent in our model needs to learn modern technology one day and to enjoy the outcome later. As the accumulated knowledge or human capital of this learning can be large in our model, the expected outcome can be large depending upon the *future* stock of human capital, regardless of the *current* stock of human capital. If people believe in much future stock of

[4] The history here means that of past state variables. In our model, these are both the current size of the modern sector (e) and the current stock of human capital (z), which are predetermined and become historical in this period. See Krugman (1991) for further discussion about the distinction of history versus expectations.

human capital, they expect a large life-time outcome and are thus willing to adopt technology today even when the current stock of human capital is small. This economy then industrializes gradually and is able to grow. In our model, neither the current size of the modern sector nor that of human capital plays any role in choosing an equilibrium path. According to Matsuyama (1991) in contrast, the external effect or knowledge cannot accumulate over time. Depending upon the parameters in that model, either history or expectations or both play a role in choosing an equilibrium. Moreover, no equilibrium path leading to a steady state in Matsuyama involves sustained growth.

Our equilibrium involves a threshold property. Our threshold is not determined by state variables. A threshold property appears in studies by both Stokey (1988), and Azariadis and Drazen (1990). Their thresholds, however, are determined by a state variable, above which the economy selects the equilibrium that is either able to introduce new products to sustain growth (Stokey) or to push the economy to develop in a better stage (Azariadis and Drazen).

This paper is organized as follows. After this introduction, we specify the basic model and analyze optimization of individuals in the next section. Then we investigate the perfect-foresight equilibrium in section 3. In section 4 we proceed to characterize the properties of equilibrium trajectories by a graphical tool. We conclude in section 5.

2. THE BASIC MODEL

2.1. *Preferences and Technologies.* In this economy, there is a continuum of risk-neutral,[5] and self-employed entrepreneurs, of which the size is constant and normalized to unity for simplicity. Each entrepreneur owns one unit of labor endowment. There is an overlapping generation. Every entrepreneur throughout his lifetime faces a constant and independent probability b of death (Blanchard 1985). A constant population thus implies that at each moment a new generation is born at the size b. The setting of a process of death and birth serves to capture the dynamic phenomenon of business closure (bankruptcy) and start-up. A new start-up generates knowledge accumulation as firms of a new generation need to acquire knowledge to start a business in a modern sector and their behavior generates a knowledge spillover.

Technology of two types produces a homogeneous commodity; they use only labor as input. The traditional type is operated under constant returns, with one unit of labor input producing y units of output. Every entrepreneur, including the new born has free access to technology of this type. An entrepreneur can also choose to adopt a modern technology. This technology has also a constant return at a point in time. Nevertheless, a modern technology is subject to an externality. Specifically, the productivity of modern technology is assumed to depend on the stock of human capital specific to this industry. This human capital is the result of learning-by-doing

[5] The result of our work is not altered if people are averse to risk. In this case, we replace y and g in equations (1) and (2) in section 2.2 by $u(y)$ and $u(g)$, with $u' > 0$ and $u'' < 0$.

or cumulative experience originating from adopting modern technology. This learning displays spillovers among firms in this industry. The accumulation of human capital is specified in Section 2.4.

We assume that the modern production function is of the functional form $g(z)$, in which z denotes the stock of human capital. This production function states that one unit of labor input produces $g(z)$ units of output. As an entrepreneur alone cannot appreciatedly affect z, his productivity at a given time is thus constant. When z is altered over time, $g(z)$ varies in the same direction. We therefore assume $g_z(z) > 0$. We also assume that $g_{zz}(z) < 0$, namely that positive externality is diminishing in z. Since $g_{zz}(z) < 0$, we impose further an upper bound A for $g(z)$. An upper bound of $g(z)$ is assumed technically for the derivation of threshold property. Intuitively, the upper bound of productivity may reflect the bounded learning-by-doing proposed by Young (1991, 1993).

2.2. *Adoption by Technology.* Adoption of technology in a developing country involves a risk as its return is generally associated with uncertainty. This condition typically hinders the incentives to adopt technology. To capture this element, we assume that if an entrepreneur i invests $\beta_i(t)\,dt$ units of flow resource cost in a time interval dt, he gains a modern technology with probability $a(\beta_i)\,dt$. As we assume $a(\beta_i)$ to be less than or equal to unity, this investment project is thus risky. Nevertheless, a greater level of β_i will surely increase the adoption probability. We therefore need the following assumptions.

We assume that $a(0) = 0$ and $a(\beta_i)$ is nonnegative, twice continuously differentiable, strictly increasing, and strictly concave for all $\beta_i > 0$. This assumption indicates that greater investment increases the probability of technology adoption, but at a decreasing rate. We assume that each individual has a common and constant instantaneous time-preference rate r. Then the stock-market value of each producer in the traditional and modern sectors satisfies, respectively,

$$(1)\qquad rV_{y_i}(t) = y - bV_{y_i}(t) + a(\beta_i(t))\left[V_e(t) - V_{y_i}(t)\right] - \beta_i(t) + \dot{V}_{y_i}$$

$$(2)\qquad rV_e(t) = g(z(t)) - bV_e(t) + \dot{V}_e,$$

in which $V_{y_i}(t)$ and $V_e(t)$ are, respectively, the expected life-time income of an agent currently working in traditional and modern industry; a variable with a dot above it denotes its time derivative. Equations like these are common in the search equilibrium literature (see, for example, Diamond 1982; Howitt and McAfee 1987; Mortensen 1989; Chen 1995), and each of them is of a form "interest rate multiplied by asset value equals flow benefits (dividends) plus expected capital gains (or losses)" (Shapiro and Stiglitz 1984). Specifically, $rV_{y_i}(t)$ in equation (1) is the instantaneous stock-market value of an entrepreneur i in traditional sector in a time interval dt. This market value consists of the sum of both instantaneous income from producing a product (y) and capital gains. There are three sources of capital gains. First, as an entrepreneur/firm is bankrupted with probability b, he receives zero life-time income instead of $V_{y_i}(t)$ in that event. Secondly, if an entrepreneur invests β_i units of flow resource cost in a time interval dt, his expected net capital gain is

$a(\beta_i)(V_e - V_{y_i}) - \beta_i$. Third, the last term reflects the variation of income over time interval dt. $rV_e(t)$ in equation (2) is the instantaneous stock-market value of an entrepreneur currently in the modern industry. Equation (2) has similar meanings to those in equation (1) for an entrepreneur in modern industry.

2.3. *Optimization of Individuals.* We proceed to investigate how an entrepreneur invests in adopting technology optimally. We denote $V_i(t) = V_e(t) - V_{y_i}(t)$ and interpret $V_i(t)$ as (life-time) value surplus. By subtracting (1) from (2) we find

$$\dot{V}_i = (r + a(\beta_i) + b)V_i(t) - [g(z(t)) - y + \beta_i(t)], \tag{3}$$

in which $\dot{V}_i = \dot{V}_e(t) - \dot{V}_{y_i}(t)$ is used. If β_i is chosen optimally, we obtain the value surplus in the following equation

$$V_i(t) = \int_{\tau=t}^{\tau=\infty} \exp[-(r + a(\beta_i) + b)(\tau - t)]\{g(z(\tau)) - y + \beta_i(\tau)\}\, d\tau. \tag{4}$$

Given the expected $V_i(t)$, we thus derive $V_{y_i}(t)$ from (1) as follows

$$V_{y_i}(t) = \int_{\tau=t}^{\tau=\infty} \exp[-(r+b)(\tau - t)]\{y + a(\beta_i(\tau))V_i(\tau) - \beta_i(\tau)\}\, d\tau. \tag{5}$$

The problem of an entrepreneur i is to maximize $V_{y_i}(t)$ in (5) by choosing investment level $\beta_i(\tau)$, given $z(t)$, $e(t)$ and the expected $V_i(t)$. The necessary and sufficient condition is

$$a_{\beta_i}(\beta_i(\tau))V(\tau) = 1, \forall \tau \geq t. \tag{6}$$

According to equation (6), an entrepreneur i invests $\beta_i(\tau)$ units of flow resource cost in technology adoption in every period $\tau \geq t$ up to the level at which the expected marginal value surplus equals the marginal cost, as long as he remains in the traditional sector. If an interior solution exists,[6] equation (6) implies a unique optimal level of investment $\beta_i = \beta_i(V_i)$, with β_i being continuous and increasing in V. The optimization faced by all entrepreneurs in the traditional sector is the same, regardless of age, since they all face the same probability per unit time. We thus drop the subscript i from now on.

2.4. *Accumulation of Human Capital and Variation of Modern Industry.* When modern technology is adopted, there is a spillover effect through learning-by-doing that increases the stock of human capital specific to this industry. As a fraction $1 - e(t)$ of the population is in the traditional industry and only people in this industry adopt technology, the human capital accumulation is thus assumed to

[6] An interior solution in equation (6) is guaranteed as long as $\lim_{\beta i \to 0} a_{\beta i}(\beta_i) = \infty$ and $\lim_{\beta i \to \infty} a_{\beta i}(\beta_i) = 0$, a sort of Inada condition. Note that $\lim_{\beta i \to \infty} a_{\beta i}(\beta_i) = 0$ is implied as $a(\beta_i)$ is concave in β_i and $0 \leq a(\beta_i) \leq 1$.

be of the following form

$$\dot{z} = z(t) G\left[\int_{e(t)}^{1} (1-b) a(\beta(t))\, di\right]. \tag{7}$$

We assume that G is nonnegative and increasing in the argument, with $G(0) = 0$. The argument in G is the average rate of technology adoption in this economy; this formulation states that the rate of growth of human capital is increasing at the average rate of technology adoption. We make this assumption because it is unlikely that the stock of human capital declines in value. Accordingly, if no resource is invested in the adopting activity ($\beta = 0$), then the accumulation of the human capital stops.

Our setup of human capital accumulation in equation (7) follows those employed in studies by Lucas (1988) and others. We could complicate the setup and introduce a small fixed rate of depreciation (δ) in human capital. With this new formulation, one difference is that z starts to de-accumulate when V is below a particular value. This complication nevertheless changes no qualitative results about economic growth and the process of industrialization to be analyzed, as long as $G > \delta$. The basic reason is that the condition dictating the threshold property and thereby the dynamics of the system continues to hold.[7] We therefore maintain the formulation in equation (7).

To complete the model, we specify how the size of the modern industry, e, varies with time. As this size increases from those who transfer from traditional industry, and decreases as a result of possible bankruptcy of firms in existing modern industry, its size thus varies according to

$$\dot{e} = \int_{e(t)}^{1} (1-b) a(\beta(t))\, di - e(t) b. \tag{8}$$

With the complete specification of the model, we proceed to analyze the equilibrium.

3. ECONOMIC GROWTH IN EQUILIBRIUM

We assume an entrepreneur to have perfect foresight about the value surplus. His perceived $V(t)$ is therefore equal to the realized $V(t)$ in equilibrium. Moreover, as optimal resources invested in individuals, $\beta(\tau)$, are equal in equilibrium because of the representative-agent construction; $\{\int_{e(t)}^{1}(1-b)a(\beta(t))\, di\}$ in both (7) and (8) becomes $(1-b)(1-e(t))a(\beta(t))$.

The perfect-foresight equilibrium of the economy is summarized by equations (3), (6), (7), and (8). As equation (6), characterizing optimal investment of adopting activity, is in turn represented by the unique function $\beta = \beta(V)$, by substituting this

[7] The way to derive the threshold property in the case with a fixed rate of depreciation is similar to that in Section A of the Appendix, with no depreciation.

unique optimal function into (3), (7), and (8) we reduce the perfect-foresight equilibrium condition of the economy to

$$\dot{V} = [r + b + a(\beta(V))]V - [g(z) - y + \beta(V)] \tag{9}$$

$$\dot{z} = zG[(1-b)(1-e(t))a(\beta(V))] \tag{10}$$

$$\dot{e} = (1-b)(1-e)a(\beta(V)) - be. \tag{11}$$

This is a system of three equations with three endogenous variables. Instead of solving these three equations algebraically, we use a diagrammatic illustration. From these diagrams we gain the essence of the model in a more intuitive way.

Although the system is in a three-dimensional space, only $\dot{z} = 0$ is a function of V, z, and e, whereas $\dot{V} = 0$ is a function of V and z and $\dot{e} = 0$ is a function of V and e. In Section A of the Appendix we explain why we can project the system of a three-dimensional space to two two-dimensional diagrams ($V - z$ and $V - e$ planes). We first draw the curve $\dot{V} = 0$ on the $V - z$ plane. Simple algebra indicates that the curve has a positive slope on the $V - z$ plane, and that the slope is decreasing in z. Moreover, the curve starts at $z = z_y > 0$ when $V = 0$, in which z_y is such that $g(z_y) = y$, and approaches $V = V^* < \infty$ when z is infinite, in which V^* is such that $\dot{V} = [r + b + a(\beta(V^*))]V^* - [A - y + \beta(V^*)] = 0$ (see the right portion of Figure 1). We next draw the curve $\dot{e} = 0$ on the $V - e$ plane, which is on the left portion of Figure 1. Although e is less than or equal to unity, the locus of $\dot{e} = 0$ is bounded by $e = 1 - b$. The reason is that $e(t) = [(1-b)a(\beta(V))]/[(1-b)a(\beta(V)) + b]$ increases in $a(\beta(V))$ and attains its upper bound $(1 - b)$ when $a(\beta(V))$ approaches unity. Moreover, this locus starts at $V = 0$ when $e = 0$. So, $\dot{e} = 0$ has positive slope on the $V - e$ plane (Figure 1).

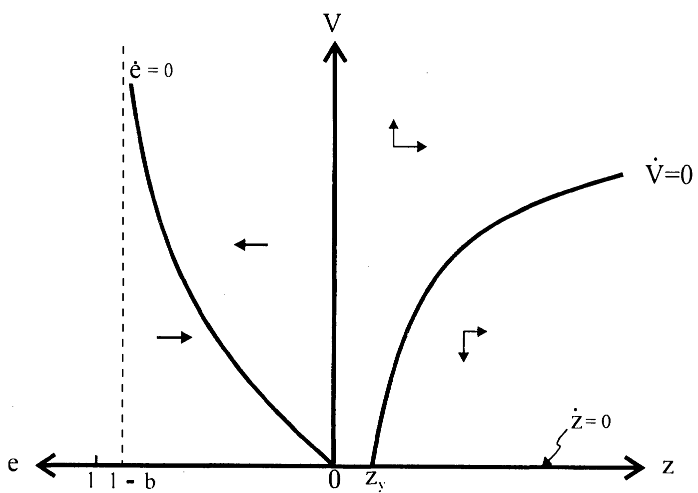

FIGURE 1

SYSTEM AND PHASE DIAGRAM

For the curve $\dot{z} = 0$, it is clear from equation (10) that, for all $0 < e < 1$ and $z > 0$, $\dot{z} = 0$ if and only if $V = 0$. That is, the curve $\dot{z} = 0$ is exactly the $z - e$ plane of positive orthant in (z, e, V) space. Since $\dot{z} = 0$ describes the way that z evolves, we project the positive $z - e$ orthant onto the $V - z$ plane. On the $V - z$ plane the curve $\dot{z} = 0$ is just the positive z-axis. (See Figure 1.)

Then, the analysis of the system reduces to that of the phase planes summarizing information in the three differential equations. That is, we analyze the phase planes. Their phase is as follows. On the right portion of Figure 1, V increases if it starts above the locus, $\dot{V} = 0$, and decreases if it starts below $\dot{V} = 0$. However, z moves only toward the right for the whole region lying above $\dot{z} = 0$. On the left side of Figure 1, e increases when it lies in the region on the right side of the locus $\dot{e} = 0$, whereas e decreases for those existing on the left side of $\dot{e} = 0$.

From the phase plane, we determine the equilibrium trajectory. We find many equilibria for a given initial state variable; some of these are able to sustain positive growth, but others are not. The initial state variables cannot restrict the way entrepreneurs form their perceived V. The possible equilibria are represented in Figure 2. Suppose the economy starts with initial state $(z(0), e(0)) = (z_0, e_0)$. The property of an equilibrium then depends upon the position at which the expected V is established. Indeed, there is a continuum of such V. The reason for multiple values of V under a given initial pair (z_0, e_0) is that V depends not only upon *current* z_0 but on *future* $z(\tau)$, $\tau > t$, no matter where e_0 is. As there can be variable $z(\tau)$, there are many expected V. Among these expected V, when its value is less than that on the locus $\dot{V} = 0$, say at V_1 in Figure 2, the equilibrium on the $V - z$ plane moves southeast and the growth rate $\dot{V}/V$ is therefore negative. In this event,

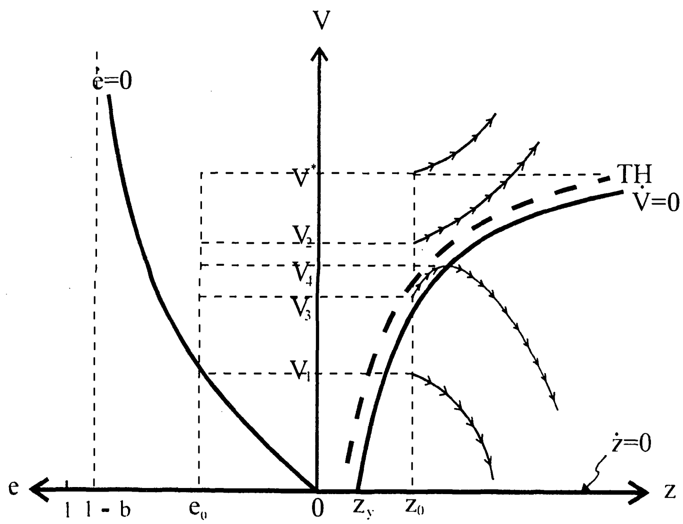

FIGURE 2

POSSIBLE EQUILIBRIUM TRAJECTORIES

the equilibrium on the $V-e$ plane will move eventually in a way that both V and e decline. Because the movement of e is more complicated, a fuller analysis will be discussed in the next section. For the time being, we focus on whether positive economic growth can be sustained. If, in contrast, the expected V under the initial (z_0, e_0) is far away from the locus $\dot{V}=0$, say at V^*, the equilibrium trajectory moves northeast and economic growth is positive and sustainable. For expected V lying between V^* and the locus $\dot{V}=0$, if it is close to V^*, say at V_2, the equilibrium trajectory behaves like those starting at V^* and the trajectory moves northeast; the economy is therefore able to sustain growth. If, however, the expected V is close to the locus $\dot{V}=0$, say at V_3, although the equilibrium trajectory moves northeast first before it strikes the locus $\dot{V}=0$ at V_4 and attains a positive economic growth rate in finite periods, it eventually moves southeast; the economy is eventually unable to sustain positive growth.

The above analysis implies the existence of a unique threshold of V for an initial $(z(0)), e(0)) = (z_0, e_0)$, above which the economy is able to sustain growth, whereas below it the economy ultimately ceases to grow. Since the same condition applies to all initial $(z(0), e(0))$, we have a locus of threshold. In Figure 2, the locus *TH* is the unique threshold given the economic structure.[8] As we mentioned above, Stokey (1988) and Azariadis and Drazen (1990) derived the threshold property. Their threshold is determined by a history or a state variable, so a state variable determines the property of their equilibrium. Our threshold, in contrast, has nothing to do with the history of either e or z, which are the only state variables in our model.

As we noted, both history and expectations play a role in selecting an equilibrium in industrialization according to Matsuyama (1991), whereas history plays no role in our model. Matsuyama does not allow an individual to vary his state once he is in one industry. Our model, however, permits an agent to choose effort to transfer to a potentially better state; moreover, this behavior generates an externality that is able to accumulate over time. It is the variation of status and the accumulated effect of learning-by-doing that isolate the unique role of expectation in our model. Furthermore, our threshold property is not shared by Matsuyama.

The economics for the role of expectations in our model is intuitive. Our equilibrium is determined by a set of forward-looking differential equations. Endowed with perfect foresight, regardless where the economy (history) starts, if an entrepreneur expects an increased V, as implied by a sizable *future* $z(\tau)$, $\tau \geq t$, in equation (8), he makes efforts to adopt a modern technology. If every entrepreneur in the traditional industry expects an increased V and therefore makes considerable effort to adopt a modern technology, the economy-wide human capital $z(\tau)$ accumulates more rapidly and the productivity of $g(z)$ is then enhanced. Expecting this, the value surplus $V(t)$ thus increases. The expectations of a greater value surplus, V, due to a large future $z(\tau)$ from technology adoption, are then self-fulfilling (see Azariadis 1981). In this case, the location of the *current* state is unimportant, and

[8] In Section A of the Appendix, we sketch the proof for the existence of a unique two-dimensional threshold in (V, z, e) space, and explain how we project the two-dimensional threshold to the one-dimensional *TH* in Figure 2.

only people's expectations matter. That is, no matter at which point both $e(t)$ and $z(t)$ exist at one time, perfect foresight leads the economy to a result that is self-fulfilling.

So far our analysis is concentrated upon sustainable economic growth. We proceed to examine the evolution of e or industrialization, and its interaction with z and V.

4. PROPERTIES OF EQUILIBRIUM

We now investigate the properties of equilibrium. We use propositions to emphasize our points. Some historical episodes are noted in support of our argument about the properties contained in our series of propositions. We first seek to know how the rate of growth, $\dot{V}/V$, varied with time.

PROPOSITION 1. *When the economy starts above the threshold in Figure 2, the rate of economic growth increases, except possibly in initial finite periods, and approaches an upper bound.*

When the economy starts above the threshold, V increases over time. Thus the condition that the rate of economic growth increases in V indicates the rate increases over time. According to equation (9) that $\dot{V}/V = [r + b + a(\beta(V(t)))] - [g(z(t)) - y + \beta(V(t))]/V$. As V increases, in a small time interval dt the rate of growth can be shown to increase by $-g_z(\partial z/\partial V)/V + [g(z) - y + \beta(V)]/V^2$; thus the growth rate may not increase in finite periods, depending whether the first term or the second term dominates. As g_z is decreasing in z and as above the threshold both V and z increase, the second term eventually dominates the first term and the growth rate increases. The rate of growth increases at a decreasing rate because $[g(z) - y + \beta(V)]/V^2$ is less than $[r + b + a]/V$, which approaches zero as V increases.[9] This condition implies an upper bound of the rate of growth.

This increasing rate of growth is not surprising. Japan's growth experience can be illustrated in terms of this result. After World War II, Japan endeavored to adopt advanced technologies from the West and to improve them. As a result, its rate of growth increased rapidly from around 5% before World War II to 9% between 1948 and 1973.

Many developing countries may not actually share an increasing rate of growth with greater industrialization. This fact does not conflict with our above result. The reason is that besides technology adoption, many factors influence economic growth. In our model we simply propose the testable hypothesis that, other things being equal, greater adoption of technology implies greater economic growth. Also, when an economy becomes mature, it cannot lean much upon technology adoption. This reason, along with others, may explain the declining growth rate of Japan after 1973.

We next characterize industrialization in equilibrium.

[9] The condition that $dV/dt = [r + b + a(\beta(V))][V - [g(z) - y + \beta(V)] > 0$ implies $[g(z) - y + \beta(V)]/V^2 < (r + b + a)/V$.

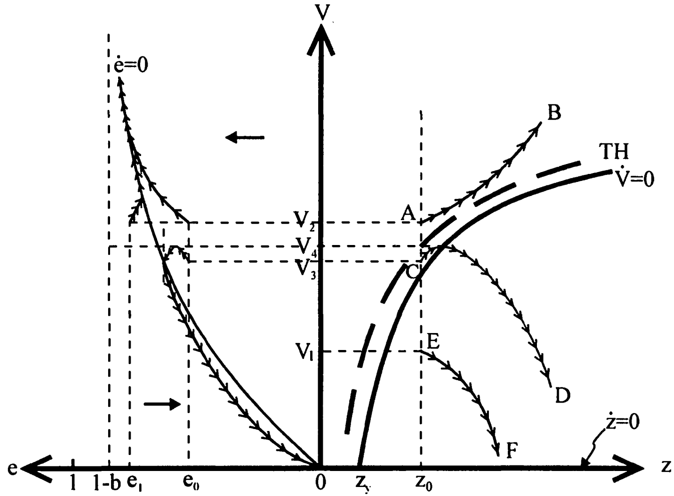

FIGURE 3

POSSIBLE TRAJECTORIES OF (e, V)

PROPOSITION 2. *When the economy starts above the threshold, it industrializes sooner or later and approaches an upper bound; otherwise, it is de-industrialized gradually and eventually locked into a state of pre-industrialization, even though it may have a positive rate of growth during several initial periods.*

We assume two possible initial states $(z(0), e(0))$, say at (z_0, e_0) or (z_0, e_1) in Figure 3, and investigate from the state (z_0, e_0) first. We explain this proposition by analyzing first the case in which the expected V lies above the threshold TH. Suppose that entrepreneurs expect a V such that the economy is at (z_0, e_0, V_2). As is illustrated in the previous section, this economy is able to sustain economic growth, and both V and z increase over time, no matter where initial e is (see right side of Figure 3). In the left segment of Figure 3 we illustrate how the process of industrialization, e, changes in response to V. Since the initial e_0 is at a location to the right of the locus $\dot{e} = 0$, e increases over time in this region. As V increases along the equilibrium trajectory AB in this situation, the trajectory in the $V-e$ plane moves northwest in finite periods and ultimately moves along the locus of $\dot{e} = 0$ and approaches $e = 1 - b$. Suppose, on the other hand, that the economy is initially at (z_0, e_1, V_2) in Figure 3, namely that the initial e is to the left of the locus $\dot{e} = 0$. Because the initial e is large, the expected arrival into the modern sector is less than the expected exiting from it; e tends to decrease in this region. As V increases along AB, the trajectory on (e, V) moves northeast in finite periods first before it strikes the locus $\dot{e} = 0$. After that, e must increase over time along $\dot{e} = 0$. Intuitively, although the expected numbers of arrivals into and exits from the modern sector are equal for a given pair of (e, V) along $\dot{e} = 0$, the expected arrivals dominate exits when V increases because entrepreneurs make a greater effort to adopt technology, and e thus increases to balance those effects. This economy industrializes sooner or later and approaches the state $e = 1 - b$.

Suppose, alternatively, that the economy starts at a place below the threshold. As illustrated in the previous section, this economy eventually ceases to grow. We assume that the economy starts in the region between the threshold and the locus $\dot{V} = 0$ in Figure 3, at (z_0, V_3). The equilibrium trajectory on the $V - z$ plane is CD. For the equilibrium trajectory on the $V - e$ plane, e increases when V increases to the level of V_4, as e_0 lies to the right of the locus $\dot{e} = 0$; the trajectory on the $V - e$ plane first moves northwest toward V_4 in finite periods. After V_4, as V declines but e still increases in later finite periods, the trajectory of the (e, V) pair moves southwest to the locus $\dot{e} = 0$. After that, the trajectory moves southeast as both V and e decrease. This trajectory may move along or below $\dot{e} = 0$. In either case, it ends at $(e, V) = (0, 0)$. Figure 3 portrays the case in which the trajectory moves below the locus of $\dot{e} = 0$. Suppose, instead, the economy is initially at (z_0, V_3) and the trajectory of (e, V) moves northeast first. Depending whether this trajectory hits $\dot{e} = 0$ when it moves northeast, we represent these two trajectories in Figure 4.

Finally, we examine the case in which the expected V lies below the locus $\dot{V} = 0$. In Figure 5, a possible trajectory EF on the $V - z$ plane is illustrated. Depending whether the initial e is at e_0 or e_1, the trajectory of (e, V) may move southwest (trajectory $M0$) or southeast (trajectory $J0$) in the first finite periods, but they then move only southeast. These two trajectories are shown in Figure 5.

We note that in the case of de-industrialization, we cannot rule out the possibility that $e(t)$ may jump down. This case happens when V reaches zero before e becomes zero. In this case there is no excess gain from using modern technology, and thereby either all or a fraction of entrepreneurs in the modern sector may destroy or give up

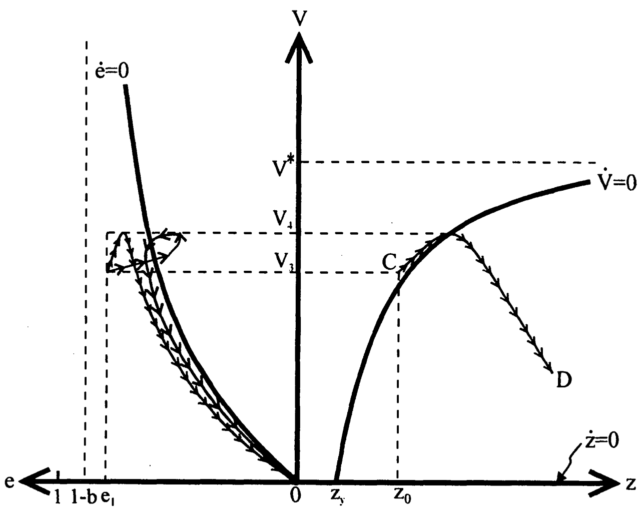

FIGURE 4

TWO POSSIBLE TRAJECTORIES OF (e, V), GIVEN THE ECONOMY IS INITIALLY AT (z_0, e_1, V_1)

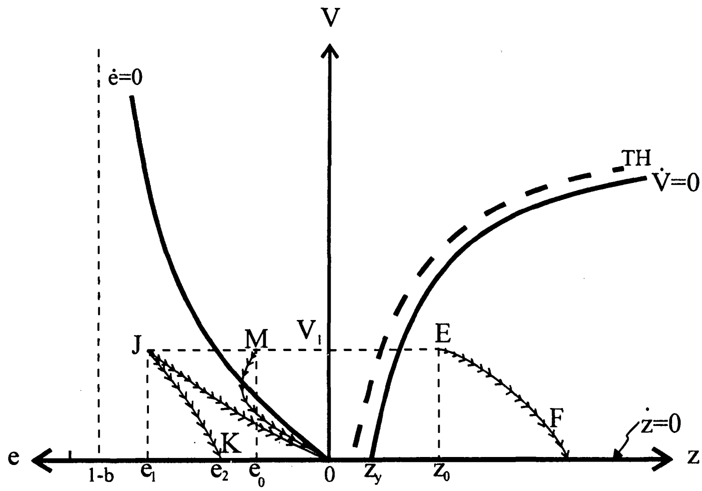

FIGURE 5

POSSIBLE TRAJECTORIES OF (e, V), GIVEN THE ECONOMY IS INITIALLY AT (z_0, e_0, V_1) OR (z_0, e_1, V_1)

modern technology and switch to use traditional technology immediately, as the switch bears no cost at all. So, e jumps down. We illustrate a possible configuration in Figure 5, in which the economy starts at (z_0, e_1, V_1). In the course when V moves from V_1 to a zero V along the EF path on the right side of Figure 5, e moves from e_1 to $e_2 > 0$ along the JK path on the left side of Figure 5. Because there is no excess gain from using modern technology when $V = 0$, these e_2 entrepreneurs may give up modern technology and use traditional technology instead. So, e_2 jumps down to 0. A similar situation occurs in the case of Figure 4, although we do not explicitly graph it.

Our above results indicate that the size of modern industry ultimately becomes zero when the economy starts below the threshold. This result, solely due to pessimistic expectations of entrepreneurs about the future, is independent of whether the economy holds positive economic growth in the early finite periods or not. When this occurs, the economy is inevitably locked into a state of preindustrialization under which the potentially greater productivity of a modern technology has no chance to work.

The result in our model that the evolution of industrialization positively coexists with a rate of economic growth differs from that of Matsuyama (1991). When the economy of Matsuyama achieves great industrialization, his economy reaches a large income in the steady state with, however, no sustainable economic growth. Although Matsuyama emphasized the aspect of steady state, whereas we focus on that of growth, the positive relation between the growth rate and the state of industrialization in our model sheds greater light on what is observed from the data. Japan's early experience after World War II mentioned above provides one example. The industrialization and growth experience of the four Asian tigers in the past two decades serves as another example.

Is a large rate of business bankruptcy necessarily bad for an economy? Governments in many economies generally believe that a large rate of bankruptcy is a bad signal for an economy. We think otherwise. An opposite result might be implied if a large rate of bankruptcy coexists at the same time as a large rate of business start-up. We characterize this element in the following proposition.[10]

PROPOSITION 3. *Suppose that there are two economies, identical except in their death/birth probability, and these two economies start at the same V above the corresponding threshold. Then the economy with a larger death/birth rate may possess a greater or smaller rate of growth.*

We provide economic grounds as follows. Intuitively, although a larger death rate reduces the speed of knowledge accumulation *per* technology adoption, it increases the number exiting from both modern and traditional sectors. For a larger death rate there is by construction a larger birth rate, and thus a larger rate of new start-up. When entrepreneurs of larger-sized new generations invest in technology adoption, the result is not only adopting *more* technology but also generating a larger rate of knowledge spillover. We show in the Appendix, Section B, that the net effect depends upon whether the positive effect of adopting *more* technology adoption on knowledge accumulation dominates the negative effect of *per* technology adoption. The rate of economic growth is thus larger if the positive effect governs the negative effect. A larger rate of business bankruptcy is thereby not necessarily bad for an economy.

A study conducted by OECD (1987, p. 258) may serve as confirmation in this regard. The study states that Japan had both the greatest rates of business closure (deaths) and start-up (births) in terms of the fraction of total number of firms among OECD countries. Combined with the fact that Japan had the greatest rate of growth in the past decades among OECD countries, this evidence supports our assertion.

Our statement in the above proposition illustrates a point that is similar to but less sophisticated than Schumpeter's (1942) creative destruction (Aghion and Howitt 1992). In a version of creative destruction, a birth process is formulated from profitable incentive and drives existing firms from the market. In our framework, both birth and death process emerge exogenously, although the incentive to enter the modern sector is income maximization. Our setting is thus less sophisticated. Nevertheless, our model still captures the substance that a large rate of bankruptcy alone is not necessarily bad for an economy.

The characteristics analyzed so far focus on the case in which the economy starts above the threshold. When the economy starts below the threshold, the economy stops growing eventually. So, any policy that is able to move or affect the expected V would help the economy to take off. After Diamond (1982), and Diamond and Fudenberg (1989), much of the literature emphasizes the role that the government can play in this respect. Subsidizing the cost of technology adoption, for example, represents one possible method because it generates an external economy. The most

[10] We thank an anonymous referee for clarifying the statement of this proposition in an earlier version of the paper.

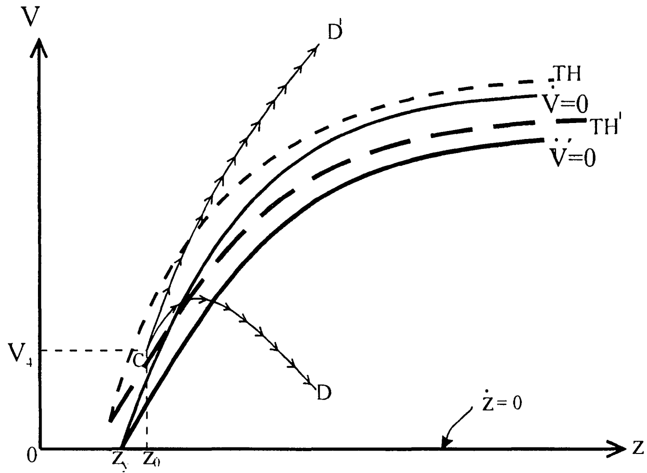

FIGURE 6

POSSIBLE RESULT OF SUBSIDIZING THE COST OF TECHNOLOGY ADOPTION

apparently successful cases of this subsidy policy are seen in Japan and South Korea in the early stage of development (see Shinohara 1982; Song 1990).

A possible result of subsidizing the cost of technology adoption is illustrated in Figure 6. Suppose that the economic structure is represented by both $\dot{V} = 0$ and the threshold TH in Figure 6. When the economy starts at (z_1, V_4) below the threshold TH, the equilibrium trajectory moves according to CD. This economy stops growing in finite periods. If, however, the government subsidizes the cost of technology adoption when the economy is at (z_1, V_4), and the economic structure becomes represented by $\dot{V}' = 0$ and the new threshold TH' in Figure 6, then, with a smaller threshold, the economy is easier to take off. Once this effect occurs, the new equilibrium trajectory may move according to CD' in Figure 6 and imply a sustainable positive rate of growth.

Finally, we must point out that government intervention may not invariously work, although the government can play a role in some rapidly growing Asian countries (see Wade 1990). For this reason some governments succeeded enhancing their economies, but others failed.

5. CONCLUDING REMARKS

We constructed a model in which we integrated both endogenous growth and industrialization. We featured the role of technology adoption in sustaining growth and achieving industrialization. Our economy contains multiple equilibria for a given initial history; only self-fulfilling expectations matter in choosing equilibrium, whereas history plays no role. The equilibrium is shown to involve a threshold property: when the economy starts above this threshold, the economy is able to sustain positive growth; otherwise, it is not. The engine of economic growth is the knowledge-like human capital specific to the learning industry and its accumulation over time when entrepreneurs invest resources to adopt technologies. Both the rate of economic growth and industrialization increase gradually over time and approach an upper bound.

We make no attempt to use our model to explain all sources of economic growth, as we simplified this model in many aspects. Like Matsuyama, we abstract from the demand side, although we know that demand may be another source of economic growth. We do so to shed particular light on the important role of technology adoption in sustaining economic growth and increasing industrialization, as many countries adopt technology successfully and grow amazingly. We also abstracted from international trade and trade policy. Researchers now acknowledge that the governmental policy on trade openness in some rapidly developing Asian countries is one reason to promote economic growth there. The role of trade policy in economic growth definitely needs to be pursued.

APPENDIX

A. In this section of the Appendix, we provide the proof for the existence of a unique two-dimensional threshold and explain the reason for being able to project the threshold to the one-dimensional locus *TH* on the $V-z$ plane in Figure 2.

Since the two-dimensional threshold will be shown to approach infinite z, we denote $p \equiv 1/z$. Then, p approaches zero when z converges to infinity. We also denote $w(p) \equiv g(z) = z(1/p)$. We therefore have $w_p = -z^2 g_z < 0$, $w_{pp} = z^3(-g_{zz} + 2g_z) > 0$ and $w(0) = A$. With this transformation of notation, we rewrite the system of equations (9)–(11) as follows.

$$(9)' \qquad \dot{V} = [r + b + a(\beta(V))]V - (w(p) - y + \beta(V)),$$

$$(10)' \qquad \dot{p} = -pG[(1-b)(1-e)a(\beta(V))],$$

$$(11)' \qquad \dot{e} = (1-b)(1-e)a(\beta(V)) - be.$$

We can check that the steady state of the system (9)′–(11)′ is $(V, p, e) = (V^*, 0, e^*)$, where V^* is defined on page 158 and e^* is the solution to $(1-b)(1-e)a(\beta(V^*)) - be = 0$. We can then write down the Jacobian of (9)′–(11)′ at the steady state. We find that the characteristic equation of the Jacobian has two negative roots, being $-[(1-b)a + b]$ and $-G[(1-b)(1-e^*)a(\beta(V^*))]$, and one positive root $r + b + a(\beta(V^*))$. This result implies that there is a two-dimensional stable manifold in (V, p, e) space; denoted $V = H(p, e)$, containing the steady state. The stable manifold is governed by the eigenvectors of the two negative roots. The eigenvector of the root $-[(1-b)a + b]$ is $(0, 0, 1)$, implying that e is a freely mobile variable, and the eigenvector of the root $-G$ is $(1, (r + b + a + G)/w_p, (1-b)(1-e^*)a_\beta \beta_V/\{G - [(1-b)a + b]\})$. These two eigenvectors thus constitute the two-dimensional threshold, on which a z corresponds to a particular V for any value of e. We depict the threshold as $V^* V_0 BC$, along with the manifold $\dot{V} = 0$, in Figure 7.

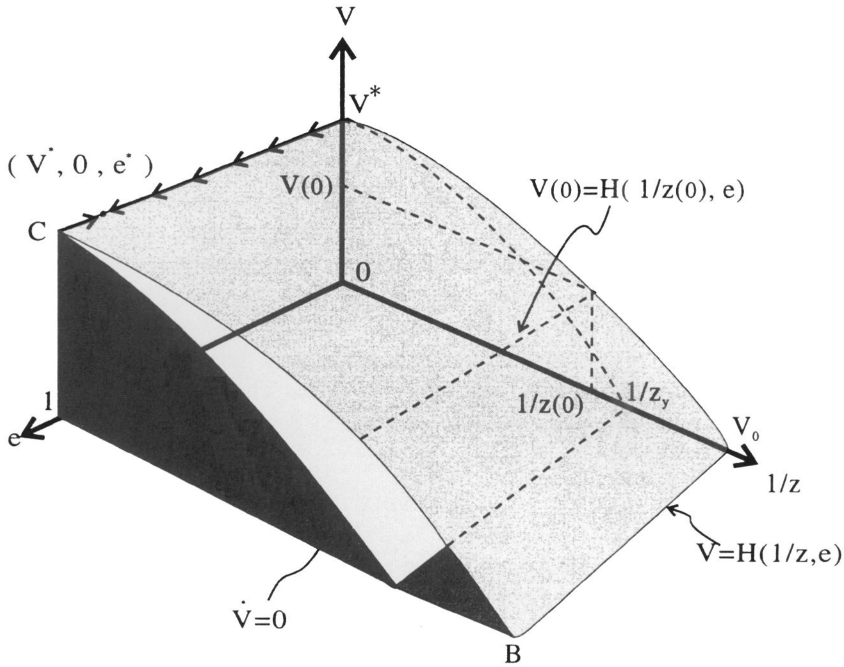

FIGURE 7

THE THRESHOLD AND ITS PROJECTION

Since V^*V_0BC in Figure 7 is a threshold, it follows that the system has the following properties. For any e and for a particular $p(0) \equiv 1/z(0)$, (1) if the expected $V(0)$ is on the threshold, that is, if $V(0) = H(p(0), e)$, the solution to the system (9)′–(11)″ converges to the steady state; (2) if the expected $V(0)$ is chosen above the manifold, that is, if $V(0) > H(p(0), e)$, the economy diverges away from the threshold in such a way that $\dot{V}/V$ is always positive and approaches an upper bound, as described in Proposition 1; (3) if the expected $V(0)$ lies below the manifold, that is, if $V(0) < H(p(0), e)$, the solution enters below the surface $\dot{V} = 0$ and V eventually becomes zero, although $\dot{V}/V$ is positive in initial finite periods before the trajectory passes the surface $\dot{V} = 0$.

Since the two-dimensional threshold and thus the dynamics of the system in $(V, 1/z, e)$ space depends only upon V and z, we can project the two-dimensional threshold onto the $V - 1/z$ plane. The one-dimensional locus V^*V_0 in Figure 7 is its projection. By transforming the $1/z$-axis to the z-axis, the projection becomes the locus TH in Figure 2.

B. In this section of the Appendix, we derive the algebra to verify Proposition 3. We first rewrite equation (9) as follows.

$$\text{(B.1)} \qquad \frac{\dot{V}}{V} = r + b + a(\beta(V)) - [g(z) - y + \beta(V)]/V > 0,$$

whose value is restricted to be positive according to the condition specified in Proposition 3. Totally differentiating equation (B.1) with respect to b, and taking into account its effect on all endogenous variables, we get

$$\text{(B.2)} \qquad \frac{d(\dot{V}/V)}{db} = 1 + a_\beta \beta_V \frac{\partial V}{\partial b} - \frac{g_z(\partial z/\partial V)(\partial V/\partial b) + \beta_V(\partial V/\partial b)}{V} + \frac{g(z) - y + \beta(V)}{V^2} \frac{\partial V}{\partial b}.$$

We will decide when equation (B.2) is positive or negative; namely under what condition the economy with a larger death/birth rate possesses a greater or a smaller rate of economic growth. First, recall that $a_\beta(\beta) = 1/V$ in equation (6) of individual optimization. So, equation (B.2) is reduced to

$$\text{(B.3)} \qquad \frac{d(\dot{V}/V)}{db} \left\{ 1 + \frac{-g_z(\partial z/\partial V)}{V} \frac{\partial V}{\partial b} \right\} + \frac{g(z) - y + \beta(V)}{V^2} \frac{\partial V}{\partial b}.$$

We note that in a time interval dt, $\partial V/\partial b < 0$ as a larger b shifts the locus $\dot{V} = 0$ downward for every z and so lowers V, and $\partial z/\partial V > 0$ as a larger value surplus induces a greater effort of technology adoption, increasing human capital. The value of the first term (the large brace) is positive, whereas that of the second term is negative. If the first term dominates the second term, equation (B.3) is positive; otherwise, it is negative.

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