Board of Governors of the Federal Reserve System

International Finance Discussion Papers

Number 642

July 1999

FROM INDOCTRINATION TO THE CULTURE OF CHANGE: TECHNOLOGICAL PROGRESS, ADAPTIVE SKILLS, AND THE CREATIVITY OF NATIONS

Murat F. Iyigun and Ann L. Owen

FROM INDOCTRINATION TO THE CULTURE OF CHANGE: TECHNOLOGICAL PROGRESS, ADAPTIVE SKILLS, AND THE CREATIVITY OF NATIONS

Murat F. Iyigun and Ann L. Owen*

Abstract: We distinguish learning in a static environment from that in a dynamic environment to show the existence of an important interaction between the development of new technologies and human capital accumulation. Since technological progress creates a more dynamic and uncertain environment, it not only increases the rewards to education and ability but also enhances adaptive skills. The latter in turn determine how effectively new technologies are utilized in production because they help the workforce to innovate and improve new technologies. Thus, the adaptive skills of a workforce are an important link with which inventions and innovations play complementary roles in technological progress. Our results suggest why countries that have comparable levels of aggregate human capital and that are in similar stages of development may differ significantly in how successful they are in implementing new technologies. They also show how the intergenerational transmission of knowledge evolves endogenously with technological change. If technology changes rapidly during the process of development, learning fosters the intergenerational propagation of adaptive skills. In contrast, if technological progress is slow during development, the education of the young reinforces the learning of long-held norms.

keywords: inventions, innovations, learning, human capital, growth.

* The authors are staff economist in the Division of International Finance, Board of Governors of the Federal Reserve System, and Assistant Professor of Economics at Hamilton College, respectively. They would like to thank David Bowman, Cevdet Denizer, Jon Faust, Dale Henderson, Michael Kremer and Andrew Levin for a number of insightful discussions and comments. The views in this paper are solely the responsibility of the authors and should not be interpreted as reflecting the views of the Board of Governors of the Federal Reserve System or of any other person associated with the Federal Reserve System. Please send all correspondence to: The Board of Governors of the Federal Reserve System, Mail Stop 23, Washington, D.C. 20551. E-mail: iyigunm@frb.gov and aowen@hamilton.edu.

"The history of science is one great confirmation of the fact that we find it exceedingly difficult to adopt a new scientific point of view or method. Thought runs again and again into the accustomed track even if it has become unsuitable and the more suitable innovation in itself presents no particular difficulties...But precisely because of this they become dragchains when they have outlived their usefulness...This opposition is stronger in primitive stages of culture than in others but it is never absent... These elements are still effective today, despite the fact that a period of turbulent development has accustomed us to the appearance and the carrying out of innovations..."

Schumpeter (1934).

1. Introduction

Is a society's receptiveness to new ideas and its success in embracing and implementing new technologies independent of its history of technological creativity? There are plausible reasons to think not. Technological change alters the environment in which learning takes place and affects the intergenerational transmission of knowledge. As economic historians and evolutionary biologists would confirm, life is vastly different when the environment is changing. Thus, it is only natural for the content of learning in a dynamic environment to differ from knowledge accumulated in static environment. If nothing else, it is clear that a changing environment fosters adaptability.[1]

Our primary motivation in this paper is to examine the implications of differentiating human capital accumulation in a static environment from that in a changing environment. In so doing, we show that there is an important interaction between the

[1] Mokyr (1992) discusses this issue: "Technological systems like all cultural systems, must have some built-in stability. Information is transmitted from generation to generation by the training of young workers, the writing of engineering textbooks, and continuous learning and mutual imitation. From the medieval peasant plowing his field, to the modern engineer using CAD to build a machine tool, conventions have evolved, and order is sustained as people cling to what they have been taught and equipment is made to conform to standards and customs. If the story ended there, however, history would be a dull tale indeed; marginal changes do not an Industrial Revolution make...life in a technologically creative world was different from that in a static economy. It is one thing to resist a once-and-for-all change in technology, quite another to resist living in a hectic and nerve-wracking world in which producers have to run to stay in place, constantly spending effort and resources searching for improvements."

development of new technology and the accumulation of human capital. Specifically, the changing environment brought about by the introduction of new technologies fosters adaptive skills. In turn, these adaptive skills allow new technologies to be implemented more profitability and create greater incentives for research and development. Adaptive skills are the result of education in a changing environment and enable workers to keep up (or prevent them from falling too far behind) with major inventions that discretely alter potential productivity. While learning-by-doing in the implementation of new technology complements adaptive skills in increasing efficiency in the long-run, an economy's stock of adaptive skills influences how efficiently a new technology is first used and, thus, reduces the need for learning in production. When inventors are rewarded with monopoly profits that are short-lived either because of potential obsolescence or patent expiration, the efficient use of new technologies soon after their introduction will be crucial in determining the incentive to invest in research and development. When adaptive skills are low, the early use of new technology will be inefficient, and although learning-by-doing would eventually allow the technology to reach a high long-run potential, inventors will not be able to profit from this eventual learning and will therefore have little incentive to engage in R&D. Thus, the ability to make a technology profitable soon after its implementation is crucial to ensuring sustained technological progress.[2]

At the heart of our effort lies an attempt to explain why some societies are successful in periodically generating and adopting new technologies while others are not.[3] While physical capital and education are important in explaining the innovative success of individual countries, cross-country differences remain quite large even after controlling for these factors.[4] Our analysis calls into question the invariance of the link between

[2]What we define as adaptive skills are somewhat comparable to the households' "capacity to absorb new technology" in Lloyd-Ellis (1999). However, in that paper, a household's absorptive capacity is dependent only on the level of skills previously achieved. In our model, the ability to adapt to new technology is a consequence of the culture of change generated by technological progress. Our definition of adaptive skills is more similar to that found in Aghion, Howitt and Violante (1999) who focus on the implications of differences in adaptability for wage inequality.

[3]A complementary finding to ours is that institutional features of the economy or "social capital" enhance growth and increase the level of per capita income. See Hall and Jones (1997) and Knack and Keefer (1997) for a discussion of this issue.

[4]For example, Tratjenberg (1999) shows that Finland and Israel rank high in terms of patents per capita, compared to the Asian tigers and a group of countries with similar GDP per capita. There has

education and human capital accumulation across time and countries, as we posit a different role for education that is dependent on current and past economic conditions. The model we present below shows that, if the process of development is accompanied by rapid technological change, the content of education also evolves endogenously to encourage technological progress. On the other hand, when technological change is slow, the education of the young reinforces the learning of long-held cultural norms.[5]

Our work is closely related to that of Young (1993). In his model, new inventions are initially implemented inefficiently, but production experience allows small innovations (learning-by-doing which increases the efficiency with which new technologies are used) to take place. Because new technology is always used inefficiently initially, the ability to innovate in the long-run is crucial for providing appropriate incentives for investing in the research and development necessary to introduce new goods. Our model also features both large-scale improvements in the aggregate technology and "microinventions" which allow for more efficient use of the existing vintage of technology. We differ from Young, however, in that inventors do not earn profits over an infinite horizon because an old technology can become obsolete and because patents expire after one generation. Thus, the efficiency with which an economy uses new technologies over a relatively short time horizon becomes important. In our model, the efficiency of new technology depends on an economy's adaptive skills–skills that are themselves influenced by the historical pattern of technological change.

This perspective allows us to make an important observation about invention and adoption of new technology. The more accustomed workers are to change, the more able they are to realize the potential of new technologies and the faster these new technologies become profitable. In contrast to Young's model in which faster technological change means new technology is initially deployed further from its potential, our model implies

also been differing rates of success in inventing and implemeting new technologies over time. In fact, Lee (1980) and Pritchett (1997) demonstrate that the standard of living has been rising consistently for only a few centuries. As we will show in what follows, this historical pattern of the growth rate could also be generated by our model–only when the adaptive skills of the workforce reach a certain level, are sufficient resources devoted to research and development to guarantee consistent progress.

[5] We still consider the transmission of this type of knowledge to be human capital accumulation because it does enhance an individual's productivity. In a related paper, Cozzi (1998) gives several examples of how an economy's culture influences its productivity.

that faster technological change translates into greater efficiency when new technology is initially implemented. Thus, advances in technology lead to more invention because exposure to new ideas makes the workforce more adept at using new technology and profits from its initial implementation higher. In our framework, it is crucial that societies have the adaptive skills to learn to make profitable use of a new technology within a finite period of time; otherwise that technology will never be introduced.

Others have also explored the idea that an economy's ability to profitably adopt a new technology depends on its resources. For example, Basu and Weil (1998) argue that an economy's capital to labor ratio determines the efficiency with which it can use a particular technology. Matsuyama (1999) also develops a model in which the economy's capital stock must be large enough in order to allow new products to be introduced, and Chen and Shimomura (1998) identify a link between self-fulfilling expectations about the economy's future human capital stock and the incentive to adopt modern technology when there is learning-by-doing with the introduction of new technology. Although, Chen and Shimomura focus on the effect of the stock of human capital on adoption of new technology, they do not explore how the human capital stock affects the incentives to invent. In a slightly different, but related, vein Acemoglu (1998) discusses how the skill composition of the work force influences the nature of the technology invented.[6]

Why would adaptive skills matter for technological progress? Here we look to the human capital literature, with Schultz (1975) providing some important empirical motivation for our assertion. He argues that education and ability are more valuable in periods of change and reviews several studies that support this view. The reasoning behind Schultz's argument is that education and ability encourage adaptability, and

[6] Our findings are also related to those of Jovanovic and Nyarko (1996). They show that workers who acquire expertise in a particular technology may never want to switch to a new superior technology because of the short-run reduction in productivity. As we discuss at the end of Section 2.3, this is a potential outcome of our model if there are consecutive periods of no new invention and workers adaptive skills erode.

In addition, Galor and Tsiddon (1997) show that intergenerational earnings mobility leads to faster growth becasue mobility allows more able individuals to concentrate in the technologically advanced sectors. In our model, mobility would also lead to faster growth if it also created an environment of change and led to more adaptive skills. It is also possible that the causation between mobility and adaptive skills would run both ways–higher adaptive skills might create a society that is more accepting of class mobility.

during periods of disequilibrium, the reward to adaptability increases. There is also evidence that technological progress increases the return to an unobservable component of skill not accounted for by education and experience.[7] Juhn, Murphy, and Brooks (1993) demonstrate that the reward to the unobservable component of skills has increased over the period 1963-1989, a period which witnessed the implementation of many new technologies. In addition, Bartel and Lichtenberg (1991) and Bartel and Sicherman (1999) show that industries that use new technologies pay higher wages to workers with the same levels of experience and education than industries that use older technology. In a complementary finding, Berman, Bound and Griliches (1994) show that industries with recent investment in R&D pay higher skill premiums. These findings support the idea that there is a component of human capital that is particularly valuable in unfamiliar circumstances. While clearly this evidence could be consistent with other theories, taken together, these studies support the idea that, at the microeconomic level, the ability to adapt to new circumstances is an important component of skill that is rewarded when technology advances. Thus, when considering human capital at the macroeconomic level, one must also consider the fact that some societies may be better at cultivating adaptability than others, making the society as a whole more adept at implementing new ideas and technology.

In what follows, we develop a three-period overlapping-generations model in which education in a changing environment produces adaptive skills. The same level of education in a static environment produces a smaller stock of adaptive skills, less human capital and lower incentives to carry out R&D. In the long-run, due to the dynamic interplay between technological progress and the accumulation of adaptive skills economies may experience either advancement to a balanced growth path with high adaptive skills and continuing invention, or stagnation, a stationary steady state with low adaptive skills and no invention. During the transition, however, technological progress takes the form of inventions in certain periods followed by innovations and improvements to existing techniques in others. These results are developed in the following 3 sections: Section

[7] Galor and Tsiddon (1997) review several other studies that support the idea that technological progress increases the return to ability (unobservable component of human capital) in addition to the ones mentioned here.

2 describes the basic model, Section 3 discusses its dynamic behavior and Section 4 concludes.

2. The Economy

2.1. Production

Consider an economy that operates in a world in which economic activity extends over an infinite discrete time. Production is carried out by a finite number of identical firms indexed by j, $j \in [0,1]$. The output of each firm, y_t^j, is a single homogenous good which can be produced using human capital, H_t, with the following technology:

$$y_t^j = (A_t^v)^j \ (H_t^j)^\gamma, \qquad 0 < \gamma < 1 \tag{1}$$

where A_t^v denotes the endogenously determined "effective" technology level of vintage v, $0 \leq v \leq t$. We assume that equation (1) exhibits constant returns to scale (CRS) with respect to all the inputs in production.[8] By definition, aggregate output at time t, Y_t, equals $\int_0^1 y_t^j \ dj$.

The labor market is competitive. Thus, the wage rate paid to human capital equals its marginal product:

$$w_t = \gamma \ A_t^v H_t^{\gamma-1}. \tag{2}$$

2.2. Individuals

Individuals live for three periods in overlapping generations and are endowed with one unit of time in every period. Each individual also has an innate ability, a^i, which increases the effectiveness of education in producing human capital. We assume that innate ability is invariant within families and we normalize the size of the population to 1. Thus, $\phi(a^i)$, the distribution of abilities, satisfies

[8] We discuss the determination of A_t^v more thoroughly in subsection 2.3.

$$\int_{\underline{a}}^{\bar{a}} \phi(a)da = 1. \tag{3}$$

where $\bar{a}$ and $\underline{a}$ denote the upper and lower bounds of the support of the ability distribution.[9] For sake of expositional simplicity, we set $\int_{\underline{a}}^{\bar{a}} a^i \phi(a)da$ also equal to one.

In the first period of life, individuals accumulate human capital by attending school. In the second period, they work in the production of the consumption good and save their income. Individuals' preferences are represented by a utility function that values consumption in the third period in a linear fashion.[10]

Consistent with available empirical evidence, we assume that individual i's human capital, h^i_{t+1}, increases with education, e^i_t, ability, a^i, and parental human capital, h^i_t. Again for simplicity, we employ a specific functional form for human capital accumulation similar to that found in Galor and Tsiddon (1997). Individual i of generation $t+1$ accumulates

$$h^i_{t+1} \;=\; \gamma(e^i_t)\;\phi(a^i,\; h^i_t) \;=\; e^i_t\;[\alpha_{t+1}a^i \;+\; \beta h^i_t], \tag{4}$$

where $0 < \alpha_{t+1} < 1$, $0 < \beta < 1$, e^i_t denotes the amount of time that individual i allocates to education when young, and where h^i_t denotes the human capital of i's parent. In addition, technological progress increases the relative return to ability because

$$\alpha_{t+1} \;=\; \alpha(g_{t+1}), \tag{5}$$

where g_{t+1}, $g_{t+1} \geq 1$, indexes the rate of invention in period $t+1$, and where $\alpha(1) \equiv \underline{\alpha}$, $\alpha' > 0$, $\alpha'' < 0$. In section 2.3, we explain more explicitly how the rate of invention affects

[9] Allowing less than perfect correlation of innate abilities will not alter the qualitative nature of the results we derive below.

[10] This assumption allows us to pin down the interest rate at the discount rate. We do this to simplify the analysis. Neither relaxing this assumption nor allowing consumption in periods prior to the third would materially affect our results.

the effective technology in use, A_t^v. To explore the evolution of human capital at this point, however, it is sufficient to note that, ceteris paribus, inventions increase A_t^v.

Taken together, equations (4) and (5) have some important implications. First, all individuals devote all of their time endowment in the first period to getting educated because education augments human capital and it has no cost. Thus, for $\forall\ a^i \in [\underline{a},\ \bar{a}]$, $e_t^i = 1$. While the assumption of equality of education across individuals and economies is certainly counterfactual, we make it to highlight a major point of our analysis: Differences in education levels explain only a portion of the differences in human capital stocks between economies. The second implication is that, holding the level of education constant, individuals will have higher levels of human capital if they live during a period of rapid growth of technology. When there are no new technologies invented ($g_{t+1} = 1$), learning and human capital accumulation may still occur. However, in a static environment, learning involves mostly the refinement and enhancement of knowledge and norms that were first learned at time 0. For lack of a better term, we call this component of human capital that is transmitted across the generations "basic" human capital. In contrast, when there is technological change, the relative importance of knowledge of the previous generation diminishes and changes in individuals' human capital are influenced more by their own ability to adapt to new circumstances.

[Figure 1 about here.]

Why does education and human capital accumulation mostly involve the intergenerational transfer of long-held norms when technological change is slow? The preceding discussion implies that, over time, the content of what is passed on from one generation to the next is comprised of not only the refinements made to knowledge that is conditional on a given set of circumstances but also that which is the culmination of operating in a changing environment. However, given that static environments do not reward the ability to adapt highly, when technological progress is slow, innate ability, a^i, gets relatively smaller weight compared to that component which contributes to the transfer of the previous generation's knowledge, h_t^i. And in that case, the intergenerational transmission of knowledge mostly serves to refine and improve existing techniques. In contrast, when there is technological change, the rewards to the ability to adapt increases, which in turn raises the relative importance of innate ability in human capital and diminishes that of knowledge passed on from the previous generation, h_t^i. Conceptually, this process is also related to the idea that static and relatively dormant environments provide individuals little in the way of experience that would be useful in challenging old beliefs and norms. Hence, the latter–regardless of their merit and validity–survive a much longer time when change is slow.[11]

For any given period time $t \geq 0$, we can rewrite (4) in the following way:

$$h_{t+1}^i \;=\; a^i \sum_{j=1}^{t+1} \beta^{t+1-j} \alpha_j \;+\; \beta^{t+1} h_0^i. \tag{6}$$

Thus, an individual's stock of human capital reflects the cumulative effect of learning that occurred in a changing environment, with greater rates of invention (higher α_t) generating more human capital. The assumption implicit in this formulation is that individuals who have experienced change find it easier to enhance their skills than those that have not. We define this component of an individual's human capital as "adaptive skills," and denote it by x_{t+1}^i.

Let s_{t+1}^i denote individual i's basic human capital. Then, it follows that

$$\begin{aligned} s_{t+1}^i \;&=\; \underline{\alpha} a^i \;+\; \beta s_t^i \;=\; a^i \underline{\alpha} \textstyle\sum_{j=1}^{t+1} \beta^{t+1-j} \;+\; \beta^{t+1} s_0^i, \\ x_{t+1}^i \;&=\; h_{t+1}^i \;-\; s_{t+1}^i \;=\; a^i \textstyle\sum_{j=1}^{t+1} \beta^{t+1-j} (\alpha_j - \underline{\alpha}) \;+\; \beta^{t+1} x_0^i. \end{aligned} \tag{7}$$

Proposition 1: *Technological inventions foster individuals' adaptive skills. That is,* $\forall a^i \in [\underline{a}, \bar{a}]$, $\partial x_{t+1}^i / \partial g_{t+1} > 0$.

[11] Lott (1990, 1999) discusses a relevant issue. He stresses education's role in indoctrinating the masses. Central to his analysis is the observation that public education allows more control over educational content. Our results, which are complementary to his, demonstrate that using public education as a tool of indoctrination is more fruitful in static environments. The recent history of former East bloc countries provide ample support. Viewed from this perspective, for example, it can be argued that the downfall of the Soviet Socialist Republic subsequent to Gorbachov's "glasnost" was inevitable.

Proof: Follows immediately from (5), (7) and $\alpha' > 0$. $\square$

What is also clear from an inspection of (6) and (7) is that the marginal return of education depends on the historic rate of technological progress. Thus, in economies that have experienced sustained periods of technological growth, education plays its most important role in enhancing the adaptive skills of future generations. In this case, education is also more effective in producing human capital overall. In contrast, when technological progress is slow, the role of education in human capital accumulation is primarily to transfer existing knowledge.

Proposition 2: $\forall t$ *s.t.* $0 < t < \infty$, *when the pace of technological inventions is relatively rapid* $\forall \tau \in [0, t]$, *education mostly enhances the intergenerational transmission of adaptive skills. In contrast, when the pace of inventions is slow* $\forall \tau \in [0, t]$, *education mostly fosters the intergenerational propagation of knowledge initially formed at time* 0, h_0^i. *That is,* $\forall a^i \in [\underline{a}, \bar{a}]$, $\partial(x_{t+1}^i / h_{t+1}^i) \, / \, \partial g_{t+1} > 0$.

Proof: Follows from equations (5)-(7) and $\alpha' > 0$. $\square$

While in the following sections we endogenize technological progress, it is helpful to consider the evolution of the economy when technological progress is exogenous. Suppose, $\forall \ t \geq 0$, $g_{t+1} = \bar{g} > 1$. Then this economy has two state variables, X_t, as defined above and aggregate basic human capital, S_t. It is straightforward to show that when g_{t+1} is constant at $\bar{g}$ and as $t \to \infty$, X_t and S_t approach their steady state values,

$$\bar{X} = \frac{\bar{\alpha} - \underline{\alpha}}{1 - \beta} \quad \text{and} \quad \bar{S} = \frac{\underline{\alpha}}{1 - \beta}, \qquad \text{where } \bar{\alpha} \equiv \alpha(\bar{g}). \tag{8}$$

and the economy achieves growth of aggregate output in the steady state proportional to $\bar{g}$. Higher levels of $\bar{g}$, generate higher levels of adaptive skills and higher levels of aggregate human capital. In the following section, we build on this framework to allow for endogenous technological progress.

2.3. The Technology

Technological progress can take two forms in our model; invention or innovation. Inventions are leaps up the technology ladder and manifest themselves in discrete jumps in the quality of machines available for producers to use. Innovations, on the other hand, are refinements that improve the utilization of existing technology.

To capture both of these types of technological progress, we allow the discovery of a new invention at time t to raise the potential productivity of the technology, λ_t^v, by increasing the quality of machines that can be used in production. Let z_t^v denote the quality of a machine which embeds technology of vintage v, and let q_t^v denote the quantity of such machines utilized in production at time t. As in Acemoglu (1998), we assume that

$$\lambda_t^v = \frac{(z_t^v \; q_t^v)^{1-\gamma}}{1-\gamma}. \tag{9}$$

Equation (9) implies that potential productivity increases with the number and quality of machines used in production. Because machines depreciate fully in one generation, in every period t, firms must purchase new machines.

Even when there are no new inventions that raise the quality of machines available to producers, technological progress can still occur through innovation that allows more efficient use of the existing vintage of machines. As we noted above, our model is based on the premise that, in any given time period t, the success with which available technologies are utilized in production depends on the adaptive skills of the labor force. In addition, experience with technology allows it to be employed more efficiently. Thus, the older the technology, the more efficient its use. The following representation captures both these elements in a rather simple fashion:

$$A_t^v \;=\; \lambda_t^v \exp\left(-\,\frac{1}{1+t-v}\,\frac{1}{1+X_t}\right), \tag{10}$$

where $t-v$ is the length of time machines with technology of vintage v have remained in use in production, and where X_t, $X_t = \int_{\underline{a}}^{\bar{a}} x_t^i \phi(a) da$, denotes aggregate adaptive skills in the production sector. Note that the specification in (10) implies

$$\lim_{(t-v)\to 0} A_t^v = \lambda_t^v \exp\left(-\frac{1}{1+X_t}\right) < \lambda_t^v \qquad \text{and} \qquad \lim_{(t-v)\to\infty} A_t^v = \lambda_t^v. \tag{11}$$

Thus, the effective use of a given technology depend positively on the aggregate adaptive skills of workers employed in production, and this relationship is strongest for newly invented technologies.[12] Nonetheless, to the extent a given technology of vintage v stays in use and does not become obsolete, the effect of adaptive skills on the use of technology phases out over time. In the long run, the productivity derived from the use of a technology, A_t^v, converges to its potential, λ_t^v. The assumptions implicit in equation (10) regarding the manner in which technology becomes efficiently employed are key to our analysis. As we note in our introduction, these assumptions are supported by broad empirical evidence about the implementation of new vintages of technology.

[Figure 2 about here.]

An interesting feature of the technology we specify is that, as in Young (1993), it leads to an economy which combines elements of Schumpeterian growth (in which

[12]History suggests that both major inventions and innovations play complementary roles in technological progress. There is, however, abundant evidence that this complementarity cannot be taken for granted. As Mokyr (1990) notes, the survival of inventions depends not only on the ability of the contemporaries to reproduce and utilize them, but also on the friendliness of the social or cultural environment. History is replete with examples of inventions that failed to be adopted earlier; their time had not yet come either because the work force was incapable of adopting them, the society was not receptive to new ideas, or because special interest groups stymied the adoption of new techniques. Da Vinci's many inventions were of the first and second kind, while the role of guilds in slowing the adoption of new techniques from the ribbon loom to shipbuilding in continental Europe during the early stages of the industrial revolution are examples of the latter.

progress manifests itself in small refinements to existing inventions) with a growth process that has more recently been examined in endogenous growth models a la Romer (1990). More specifically, note that when a technology remains in use more than one period, the bulk of economic progress in periods following the invention of the technology is a result of applying old knowledge more efficiently. That is, shifts in the production possibility frontier in such periods arise mainly from a higher degree of familiarity with a technology and from innovations that are designed to make current practices more efficient. In contrast, most of the production gains in periods in which a new technology is actually invented are generated due to the newness and superiority of the technology, in spite of the fact that its inaugural use will inherently be inefficient.

Similar to the approach taken in Aghion and Howitt (1992) and in Grossman and Helpman (1991), we assume that new invention moves the quality per machine one step up the quality ladder. In particular, when there is an invention of the next generation of technology, the quality of each machine, z_t increases such that $z_t = \bar{g} z_{t-1}$, where $\bar{g} > 1$. Thus, the decision of a firm j, $j \in [0,\, 1]$, is

$$\max_{q_t^{v,j},\, H_t^j} \; (A_t^v)^j \; (H_t^j)^\gamma \; - p_t^v q_t^{v,j} - \; w_t H_t^j, \tag{12}$$

where

$$(A_t^v)^j \; = \frac{(z_t^v q_t^{v,j})^{1-\gamma}}{1-\gamma} \; \exp\left(- \frac{1}{1+t-v} \, \frac{1}{1+X_t^j} \right), \tag{13.1}$$

and where p_t^v denotes the price of a machine vintage v. The solution to this problem yields, $\forall \; j \in [0,\, 1]$,

$$q_t^{v,j} = \left[\frac{z^{1-\gamma}}{p_t^v} \; (H_t^j)^\gamma \right]^{\frac{1}{\gamma}} \tag{13}$$

As we describe in the next section, at any given time t, a single firm will own the patent for the newest technology and sell machines that embed this technology to consumption goods producers. Consequently, given that the demand for machines is isoelastic, the profit maximizing monopoly price is a constant markup over marginal cost, $c > 0$. Therefore, given the specifications above, $p = c/(1-\gamma)$, for all machines which embed the newest technologies. For older vintages of technology, we assume that any prior patents have expired, the blueprints are readily available, and any firm can produce machines that embed old technology at the constant marginal cost, c.[13]

Given that older vintages of technology are always available at a lower price, there is no guarantee that firms will prefer to buy the newest technology at a monopoly price. Firms will only be willing to pay a premium for new technology if the resulting increase in efficiency is large enough. Since the stock of adaptive skills of the labor force determine how efficiently the new technology is implemented, this will only be the case if adaptive skills, X_t, $X_t \equiv \int_0^1 X_t^j \phi(j)dj = \int_{\underline{a}}^{\bar{a}} x_t^i \phi(a)da$, are above a threshold, $\tilde{X}_t^v$, $\tilde{X}_t^v = \left\{ \left(\frac{t-v}{1+t-v} \right) / \left(\frac{1-\gamma}{\gamma} \right) [\ln \bar{g} + \ln(1-\gamma)] \right\} - 1$, $\forall\, j \in [0,\, 1]$.

In any given time period t, if the adaptive skills of the labor force are less than or equal to this threshold, then the effective productivity of firms using the new technology will not be large enough to warrant purchasing it at a monopoly price. In contrast, if the adaptive skills of the labor force are higher than this threshold, firms will find it worthwhile to employ the newest vintage of machines in production. In that case, even though machines with the next best technology are available at marginal cost, firms would prefer to buy the machines with the latest technology at a markup over marginal cost. As a result, in any given period t, the introduction of new technologies makes the old technology obsolete.

Note that $\tilde{X}_t^v$ is lowest when $t-v = 1$, or, in other words, when firms are evaluating newly invented technology against technology that is only one generation old. $\tilde{X}_t^v$ rises when the existing technology ages. Thus, periods in which there are no new inventions decrease the attractiveness of implementing new production technology in the future for two distinct reasons. First, greater experience with the old technology allows producers

[13] We have chosen to maintain a constant marginal cost for machine production to keep the analysis focused on the relevant dynamics. If we were to allow the cost of machine production to vary over time, it would be difficult to establish the direction of the change on theoretical grounds. On the one hand, increased sophistication of the technology would argue for an increasing cost, but, on the other hand, increased production efficiency would suggest that costs should decrease as technology advances.

to use it more efficiently, making it less attractive to adopt new technology, even though the new technology has greater long-run potential.[14] Second, without new invention, the adaptive skills of the labor force decline, decreasing the efficiency with which the new technology would be implemented. We next turn to describing the R&D process that produces new technology.

2.4. Equilibrium R&D Effort

Inventions are the result of R&D carried out by research firms which use the final consumption good as the only input. In all time periods, there are a finite number of R&D firms, N_t, who behave competitively.[15] Let I_t denote the economy-wide probability that a new invention will actually occur in any given period t. We assume that I_t depends positively on aggregate resources spent on R&D:

$$I_t = \min\left[I\left(\omega_t\right),\ 1\right], \tag{14}$$

where ω_t is the aggregate resources spent on R&D in period t. We assume $I(0) = 0$, $I^{'} > 0$, $I'' \leq 0$, and that there exists $\omega_t = \tilde{\omega}$ such that $I_t = 1$. This assumption on $I(.)$ ensures that with a large enough amount of resources spent on R&D, aggregate invention will occur with certainty. This is similar to the arguments in Grossman and Helpman (1991) and Acemoglu(1998) who rely on a law of large numbers to ensure

[14] Because individuals in our economy are finite lived and do not have altruistic motives, firms (which are owned by individuals) are only concerned about maximizing current profits. Even if firms did have an infinite horizon, however, they would never choose to take a current period loss to implement new technology today with the hope that it will eventually return higher profits in the future as adaptive skills of the labor force increase and the costs of the technology decrease. The reason is that firms behave atomistically and do not consider their impact on adaptive skills or their effect on future inventive activity when they consider implementing a new technology. If firms believed that a newly invented technology might become profitable in the future, they would always choose to defer implementation of the new technology until a later period when its efficiency were higher and costs lower. However, because entrepreneurs lose their monopoly rights over the new technology after one generation, they will not be able to profit from delayed implementation of the technology and will therefore choose not to devote time to developing a technology that, because of the low level of adaptive skills of the labor force, they know will not be implemented. Thus, even if firms had an infinite horizon, delaying implementation of a technology until it becomes profitable would never be an equilibrium outcome.

[15] More on which below.

that technology is advanced in every period. In our formulation, however, we allow for aggregate uncertainty when the R&D sector is relatively small.

If aggregate inventive activity is successful in advancing the economy-wide level of technology in use, the probability that any given R&D firm lands the monopoly rights to sell machines with the new technology depends on the relative share of resources the firm spends on R&D, ω_t^n/ω_t, $(n = 1, 2, 3, ..., N_t)$. Put differently, conditional on the fact that an invention has occurred in any given period t, the odds of a particular R&D firm being the inventor of that new technology depends positively on the ratio of its R&D expenditures to that in aggregate. We also assume that patents expire after one generation. Thus, if the technology does not become obsolete after one period, consumption goods firms can replace existing machines by producing them at their marginal cost, c. (Because the machines depreciate fully in one generation, producers must purchase new machines in every period.) The decision of an R&D firm, n, $n = 1, 2, 3, ..., N_t$, is

$$\max_{\omega_t^n} \; I_t \pi_t \frac{\omega_t^n}{\omega_t} \; - \; B\omega_t^n, \tag{15}$$

where

$$\pi_t \; = \; \gamma \left[\left(\frac{1-\gamma}{c} \right)^{1-\gamma} \exp\left(-\frac{1}{1+X_t} \right) \; z_t^{1-\gamma} \; H_t^{\gamma} \right]^{\frac{1}{\gamma}} \; . \tag{16.1}$$

and where $I_t \pi_t (\omega_t^n/\omega_t)$ denotes the expected monopoly profits and B, $B > 0$, is the marginal cost of the R&D effort in terms of the consumption good. Given that all R&D firms are identical, the solution to this problem, n, $\forall n = 1, 2, 3, ..., N_{t,}$, is given by

$$\omega_t^* = \frac{1}{B} \frac{I_t \pi_t}{N_t}. \tag{16}$$

As equation (16) implies, aggregate R&D effort, ω_t, $\omega_t = \omega_t^* N_t$, is increasing in the monopoly profits of invention.[16] Those in turn depend on the stock of adaptive skills,

[16]As we note above, we assume that there is free-entry into research and development by relatively small firms. Those firms ignore their impact on both the economy-wide probability of success in generating new inventions and the total number of R&D firms (which in turn affect the conditional odds of landing monopoly rights). If there had been one large firm engaged in R&D, it would have taken

X_t, and aggregate basic human capital, S_t. As also implied by (16), the intensification of research and development activity might be related to more firms deciding to invest in R&D. This result would be consistent with Sokoloff and Kahn (1990) who discuss the historical pattern of entrepreneurial activity which eventually led to inventions. Late-18th and early 19th century patent data indicate that it was the broadening of the entrepreneurial pool, rather than the concentration of inventions in the hands of a limited group of researchers and professional inventors, that led to rapid technological change in the United States in the 19th century.

3. The Dynamics

In any given period t, the stock of aggregate adaptive skills, X_t, through its effect on the profitability of implementing new technology, determines the aggregate research effort, which in turn influences the probability of invention, I_t. Invention, then, influences the adaptive skills of the next period, X_{t+1}. There are three state variables in our economy: quality per machine, z_t, aggregate adaptive skills, X_t, and basic human capital, S_t, where

$$z_{t+1} = g_{t+1}\, z_t = g(z_t,\ X_{t+1},\ S_{t+1})\, z_t \ ,$$

$$X_{t+1} = \alpha[g(z_t,\ X_{t+1},\ S_{t+1})] - \underline{\alpha} + \beta X_t \ , \tag{17}$$

$$S_{t+1} = \underline{\alpha} + \beta S_t \ .$$

The evolution of the economy will be history dependent, and in any given period, t, the dynamic system will be in one of three possible regimes. In this section, we first informally discuss the three regimes and then more formally characterize the long-run equilibrium of the economy in propositions 3 and 4. The values of the three state

into account the effect of changes in its R&D resources, ω_t, on the probability of invention, I_t, but the qualitative nature of our main result–that equilibrium resources spent on R&D is an increasing function of adaptive skills, X_t–would have been unaffected. Similarly if there had been barriers to entry into the R&D sector which would have restricted the number of firms engaged in research and development, we would have had to consider a game-theoretic solution but again the qualitative nature of our result would have remained intact.

variables $(z_t,\ X_t,\ S_t)$ will determine which phase the economy is in.

(I) One possibility for this economy is that the values of the three state variables do not generate high enough profits to prompt firms to invest resources in the discovery of new technologies. Consider the case in which $X_t \leq \tilde{X}_t^v$. Given that monopoly profits equal zero when the adaptive skills of the labor force, X_t, is less than or equal to $\tilde{X}_t^v$, it is clear that $X_t > \tilde{X}_t^v$ is a necessary and sufficient condition for some positive amount of resources to be devoted to R&D activity, $\omega_t > 0$. Only in that case will there exist some positive probability that an invention will actually occur (i.e., $I_t > 0$). Thus, defining the set of all combinations of the three state variables that are associated with no inventive activity as

$$\underline{\mu}_t^v = \left\{(z_t,\ X_t,\ S_t)\ \middle|\ X_t \leq \tilde{X}_t^v\right\}, \tag{18}$$

we note that, since $I(0) = 0$, there is no aggregate uncertainty. Thus, when $(z_t,\ X_t,\ S_t) \in \underline{\mu}_t^v$, there is no technological progress, $g_t = 1\ \forall t$, adaptive skills of the labor force, X_t, converge towards zero, S_t converges to its steady state, $\bar{S} = \underline{\alpha}/(1-\beta)$, and z_t remains unchanged. There may be multiple steady states in this phase, each associated with the same X_t and S_t, but different levels of z_t. Given that in this regime the adaptive skills of the labor force deteriorate, and that, in turn, leads to a further erosion of the incentive to invent new technologies, once adaptive skills erode sufficiently to allow an economy to enter this regime–in which $X_t \leq \tilde{X}_t^v$–it never escapes.

It is important to reiterate, however, that even in this relatively stagnant environment, there will be human capital accumulation during the transition to the steady-state. Thus, choosing to get educated may remain optimal as its return may still be rising during transition.[17] But as proposition 2 indicates, the role of education in an environment in

[17]In our simple framework, getting educated is feasible and optimal for everyone at all times, as we have chosen to assume that there is no cost of education. Alternatively, we could have assumed that education has an opportunity cost in which case, even with no technological progress, a few additional standard assumptions would generate the result that the fraction of individuals who would have chosen to get educated would have risen during the transition to the steady state. Under this alternative, it might be possible for adaptive skills to increase beyond $\tilde{X}_t^v$ as education increases and the economy could escape this regime through educational expansion. However, it would still be the case that we

which adaptive skills are deteriorating is mostly confined to the intergenerational transfer and propagation of human capital which was initially formed in the early periods of development and that is conditional on the existing level of technology.

(II) A second possibility for the economy is that successful invention is profitable enough to divert some resources to R&D activity but one in which total resources devoted to R&D remain relatively small so that $0 < I_t < 1$. In particular, let μ_t^v denote the set of triplets $(z_t,\ X_t,\ S_t)$ such that $0 < I_t < 1$:

$$\mu_t^v = \{(z_t,\ X_t,\ S_t)\ \mid I_t \in (0,1)\ \} \tag{19}$$

Thus, in the second regime, there is aggregate uncertainty. In this phase, aggregate success leads to more adaptive skills, which then lead to a higher probability for success in the next period. On the other hand, bad luck leads to erosion of adaptive skills, lower expected profitability of invention, and therefore fewer R&D resources and a lower probability of success in the next period. An economy in this regime needs to be lucky to succeed, but economies with more adaptive skills will have a higher probability of success. While S_t converges to its steady state level, $\bar{S}$, there are no steady state values for X_t and z_t in this regime. In proposition 4, however, we show that an economy will never remain in this phase in the long-run.

(III) A third possibility for the economy is that the R&D sector becomes sufficiently large so that $I_t = 1$. In this case, as in (I), there is no aggregate uncertainty. New machines will replace old machines in every period. Let $\bar{\mu}$ denote the set of triplets (z_t, X_t, S_t) such that $I_t = 1$. That is,

$$\bar{\mu} = \{(z_t,\ X_t,\ S_t)\ \mid I_t = 1\ \} \tag{20}$$

Once an economy enters this third phase, the system asymptotically converges to a balanced growth path (BGP). Along the unique balanced growth path, there is invention

could define regime (I), as above, to be combinations of our state variables that generate $X_t \leq \tilde{X}_t^v$ when $e_t = 1$, and the analysis of the dynamics of our model would go through with minor modifications.

in every period ($g_t = \bar{g} > 1, \forall t$), z_t grows at the constant rate $\bar{g}$, adaptive skills approach a steady state value, $\bar{X}$, which equals $(\bar{\alpha} - \underline{\alpha})/(1-\beta)$, and S_t approaches $\bar{S} = \bar{\alpha}/(1-\beta)$. We discuss the balanced growth path more formally in proposition 3.

To formalize the long-run dynamic properties of our model we present propositions 3 and 4. Proposition 3 discusses the behavior of the economy once it reaches either regime (I) or (III) and proposition 4 shows that, in the long-run, an economy will either converge to a no-growth steady state in regime (I) or the endogenous growth path in regime (III).

Proposition 3: *(i)* $\forall$ $(z_0, X_0, S_0) \in \underline{\mu}_0^0$, $\exists$ *a unique steady state in which no resources are allocated to R&D. As a result, there is no invention in any period t,* $\forall t$, $g_t = 1$, *aggregate stock of core human capital,* S_t, *equals* $\bar{S} = \underline{\alpha}/(1-\beta)$, *and aggregate adaptive skills,* X_t, *equal zero.* $\forall$ $(z_0, X_0, S_0) \in \underline{\mu}_0^0$, *the economy converges to this steady state.*

(ii) $\forall$ $(z_0, X_0, S_0) \in \bar{\mu}$, $\exists$ *a unique balanced growth path (BGP) where a new generation of machines is invented in every period t so that,* $\forall t$, $g_t = \bar{g}$, *and where the aggregate stock of core capital,* S_t, *aggregate adaptive skills,* X_t, *are constant.* $\forall$ $(z_0, X_0, S_0) \in \bar{\mu}$, *the economy settles asymptotically on the balanced growth path (BGP) as* $t \to \infty$.

Proof: See Appendix.

Proposition 4: *For any* (z_0, X_0, S_0), *the economy will either converge to the endogenous growth path in which* $g_t = \bar{g} > 1$ $\forall t$, *or will converge to the no-growth steady state in which* g_t=1 $\forall t$.

Proof: Proof of this proposition follows directly from the fact that regime (II) is a transient state, while $\bar{\mu}$ and $\underline{\mu}_t^v$ are ergodic sets. □

Taken together, Propositions 3 and 4 characterize the long-run dynamics of our model. An economy may spend several generations in the second regime in which major technological advances may or may not occur. In this regime, a period of new invention raises the probability that a new invention will occur in the next period, but failure to invent lowers the probability of future invention due to the erosion of adaptive skills and the resulting reduction in resources devoted to research and development. However, because there is a positive probability that an economy will leave this second regime and never return, the economy eventually settles down to asymptotically reach balanced growth in regime (III) or a no-growth steady state in regime (I).

4. Conclusion

The innovation in this paper is the incorporation of adaptive skills into a model of endogenous growth. We show how the stock of adaptive skills, by influencing the efficiency with which new technology is implemented, affects the resources devoted to research and development and, ultimately, the probability of advancement measured by productivity growth. In turn, technological progress feeds back into the formation of adaptive skills of the next generation.

Holding the stock of adaptive skills constant, our model is very similar to that of Young (1993). However, the ability to make efficient use of available technology rather quickly is important when profits from invention are not accrued over an infinite lifetime–all the more so if new inventions have the potential to make old technologies obsolete. Thus, economies with higher levels of adaptive skills will promise higher profits to inventors and experience more technological progress and faster growth.

In our simple model, R&D success makes it possible to climb up the technology ladder in uniform, predictable steps. However, in reality, the research and development process is one in which advances in technology are not likely to take the form of such predictable outcomes. One possible extension of our model is to allow adaptive skills to reduce the inherent uncertainty of research and development by increasing the likelihood that new inventions can be put to productive use. This is a fruitful area for further research.

5. Appendix

- *Proof of Proposition 3:*

(i) $(z_0,\ X_0,\ S_0) \in \underline{\mu}_0^0 \Rightarrow X_0 \leq \tilde{X}_0^0$, and the initial values of the three state variables do not generate high enough profits to prompt any resources to be devoted to R&D. As a result, $\forall n = 1, 2, 3, ..., N_t$, $\omega_t^* = 0 \Rightarrow I(0) = 0$, and there is no aggregate uncertainty. Given that $g_1 = 1 \Rightarrow \alpha_1 = \underline{\alpha} \Rightarrow X_1 < X_0 \leq \tilde{X}_0^0 < \tilde{X}_1^1$, we guarantee that there is no technological progress, $\forall t \geq 0$, and $g_t = 1\ \forall t \geq 0$. Consequently adaptive skills of the labor force, X_t, converge towards zero, S_t converges to its steady state, $\bar{S} = \underline{\alpha}/(1-\beta)$, and $z_t = z_0\ \forall t \geq 0$.

(ii) $(z_0,\ X_0,\ S_0) \in \bar{\mu} \Leftrightarrow \omega_0^* N_0 \geq \tilde{\omega} \Leftrightarrow I_0 = 1$. Given that $I_0 = 1 \Leftrightarrow g_1 = \bar{g} > 1 \Rightarrow z_1 > z_0$, $X_1 > X_0$, and $S_1 \geq 0$. Thus, as $t \to \infty$, there is invention in every period ($g_t = \bar{g} > 1$, $\forall t$), z_t grows at the constant rate $\bar{g}$, adaptive skills approach a steady state value, $\bar{X}$, which equals $(\bar{\alpha} - \underline{\alpha})/(1-\beta) > 0$, and S_t approaches $\bar{S} = \bar{\alpha}/(1-\beta) > \underline{\alpha}/(1-\beta)$. □

6. References

Acemoglu, D. (1998). "Why Do New Technologies Complement Skills? Directed Technical Change and Wage Inequality," *Quarterly Journal of Economics,* 113 (4), November, 1055-89.

Aghion, P. and P. Howitt. (1992). "A Model of Growth through Creative Destruction," *Econometrica*, 60, March, 323-51.

Aghion, P., P. Howitt, and G. Violante. (1999). "Technology, Knowledge and Inequality," mimeo.

Bartel A. P. and F. R. Lichtenberg. (1991). "The Age of Technology and Its Impact on Employee Wages," *Economic Innovation: New Technology*, 1 (3), 215-31.

Bartel A. P. and N. Sicherman. (1999). "Technological Change and Wages: An Interindustry Analysis," *Journal of Political Economy*, 107 (2), April, 285-325.

Basu, S. and D. N. Weil, (1998). "Appropriate Technology and Growth," *Quarterly Journal of Economics*, 113 (4), November, 1025-1054.

Berman, E., J. Bound, and Z. Griliches. (1994). "Changes in the Demand for Skilled Labor within U. S. Manufacturing," *Quarterly Journal of Economics*, 109 (2), May, 367-97.

Chen, B. and K. Shimomura. (1998). "Self-Fulfilling Expectations and Economic Growth: A Model of Technology Adoption and Industrialization," *International Economic Review*, 39 (1), February, 151-170.

Cozzi, G. (1998). "Culture as a Bubble," *Journal of Political Economy*, 106 (2), April, 376-94.

Galor, O. and D. Tsiddon. (1997). "Technological Progress, Mobility and Economic Growth," *American Economic Review,* 87 (3), June, 363-82.

Grossman, G. M. and E. Helpman. (1991). "Quality Ladders in the Theory of Growth," *Review of Economic Studies*, 58, January, 43-61.

Hall R. and C. I. Jones. (1997). "Levels of Economic Activity Across Countries," *American Economic Review,* 87 (2), May, 173-77.

Jovanovic, B. and Y. Nyarko. (1996). "Learning by Doing and the Choice of Technology," *Econometrica*, 64 (6), November, 1299-1310.

Juhn, C., K. M. Murphy and B. Pierce. (1993). "Wage Inequality and the Rise in Returns to Skill," *Journal of Political Economy,* vol. 101, no. 3, 410-42.

Knack, S. and P. Keefer. (1997). "Does Social Capital Have an Economic Payoff? A Cross-Country Investigation," *Quarterly Journal of Economics*, 112 (4), November, 1251-88.

Lee, R. D. (1980). "A Historical Perspective on Economic Aspects of the Population Explosion: The Case of Preindustrial England," in R. A. Easterlin, ed. *Population and Economic Change in Developing Countries*, (Chicago: University of Chicago Press).

Lott, J. (1990). "An Explanation for Public Provision of Schooling: The Importance of Indoctrination," *Journal of Law and Economics, Vol.* 33, April, 199-231.

Lott, J. (1999). "Public Schooling, Indoctrination, and Totalitarianism," *Journal of Political Economy,* forthcoming.

Lloyd-Ellis, H. (1999). "Endogenous Technological Change and Wage Inequality," *American Economic Review,* 89 (1), March, 47–77.

Matsuyama, K. (1999). "Growing Through Cycles," *Econometrica*, 67 (2), March, 335-347.

Mokyr, J. (1990). *The Lever of Riches*, (New York: Oxford University Press).

Mokyr, J. (1992). "Technological Inertia in Economic History," *Journal of Economic History,* 52 (2), June, 325-38.

Pritchett, L. (1997). "Divergence, Big Time," *Journal of Economic Perspectives,* 11 (3), Summer, 3-17.

Romer, P. M. (1990). "Endogenous Technological Change," *Journal of Political Economy,* 98 (5), October, 571-602.

Schultz, T. W. (1975). "The Value of the Ability to Deal with Disequilibria," *Journal of Economic Literature,* 13 (3), 827-46.

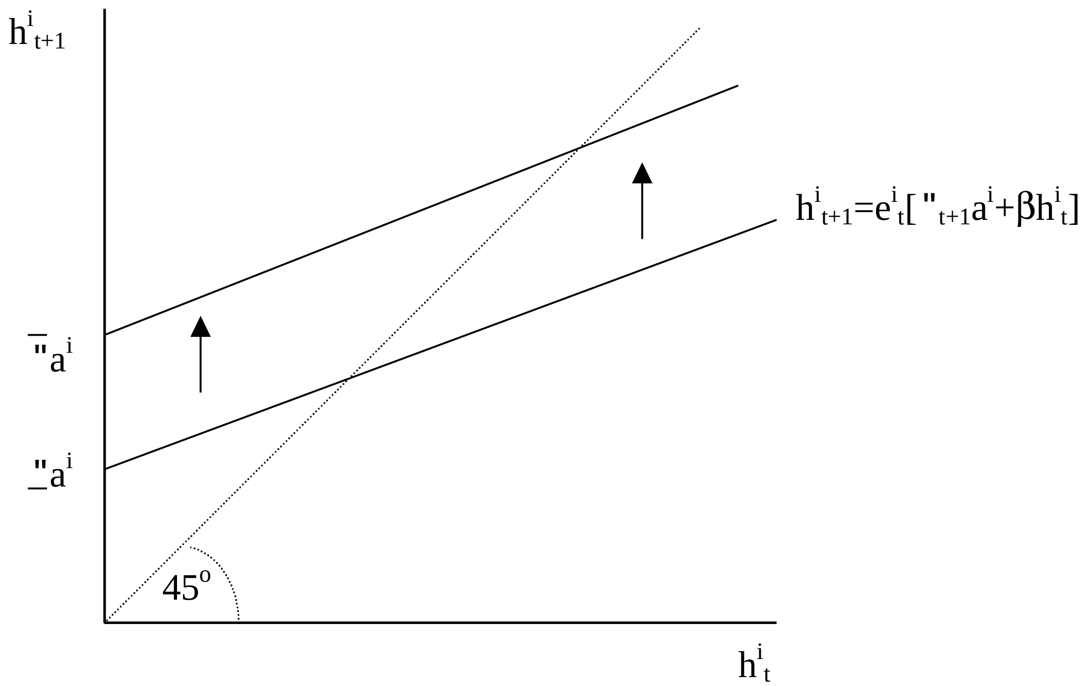
Schumpeter, J. A. (1934). *The Theory of Economic Development,* (London: Geoffrey Lumberlege, Oxford University Press).

Sokoloff, K. L. and B. Z. Khan. (1990). "The Democratization of Invention During Early Industrialization: Evidence from the United States, 1790-1846," *Journal of Economic History,* 50 (2), June, 363-78.

Tratjenberg, M. (1999). "Innovation in Israel 1968-97: A Comparative Analysis Using Patent Data," NBER Working Paper Series, March, No: 7022.

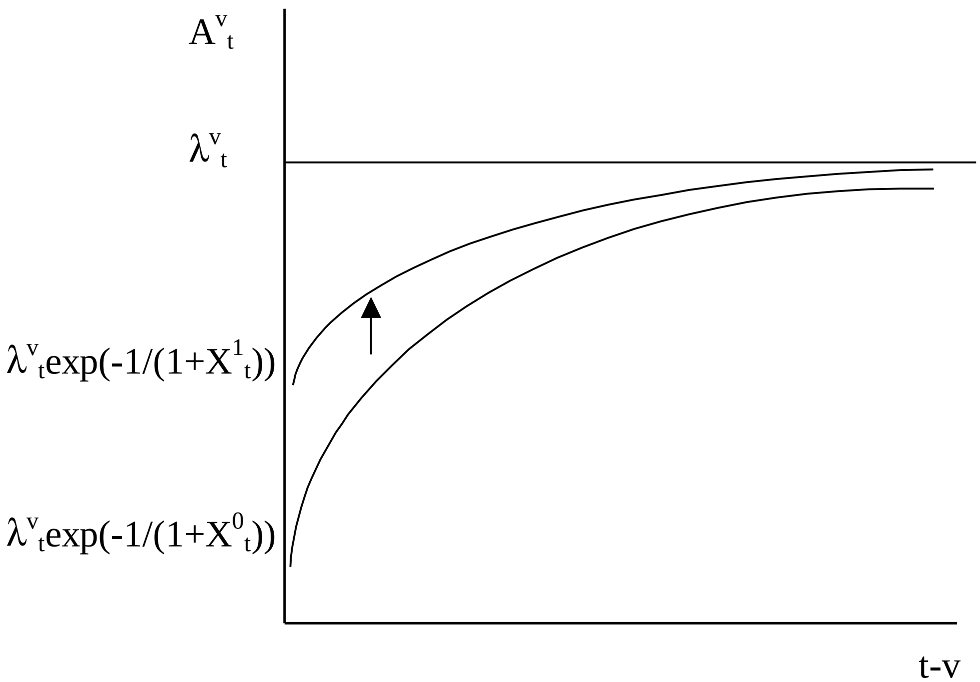
Young, A. (1993). "Invention and Bounded Learning by Doing," *Journal of Political Economy,* 101 (3), June, 443-72.

Figure 1



Technological Change and Human Capital Accumulation

Figure 2



The effect of Adaptive Skills on Technology
$(X^1_t > X^0_t)$