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Technology adoption, education and immigration policy

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Abstract

This paper explores a two-period model with complementarities between investment in/adoption of new technologies and human capital accumulation/investment in education. Workers invest in education in the first period and in the second period, entrepreneurs decide whether or not to adopt a new technology. Multiple rational expectation equilibria exist: if workers believe that a large (small) fraction of entrepreneurs will adopt the new technology next period, then their return to education will be high (low) and accordingly the level of investment in education will be high (low) too. Equivalently, entrepreneurs will adopt the new technology if the level of education is sufficiently high. Two policies are considered for ensuring that a welfare improving high-technology equilibrium will prevail, namely educational subsidies and immigration of high-skilled workers. A key result is that a commitment to immigration of high-skilled is sufficient to ensure new technology adoption.

JEL classification: F22; O14; J24; O33; D24
Keywords: Educational subsidy; Human capital; Technology adoption; Immigration policy; Rational expectation equilibrium

1. Introduction

Recent empirical evidence suggests that there exist complementarities between investment in/adoption of new technologies and human capital accumulation/investment in education and that educated workers have a comparative advantage in acquiring and implementing new technologies (Goldin and Katz, 1996; Bartel and Lichtenberg, 1987).

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This complementarity between technology and education can lead to a 'simultaneity' effect in the adoption of new technologies and investment in education. Since education increases an individual's ability to acquire, absorb and implement new technologies, investment in education increases returns from adoption of new technologies relative to the old technology. On the other hand, adoption of new technologies increases both demand and wages for educated workers relative to the rest of the workforce (see Krusell et al., 2000).[1] Thus, workers' decisions to invest in education and entrepreneurs' decisions to adopt a new technology may be interdependent.

Our paper formally models this interdependence between investment in education and adoption of new technologies and explores the effects of immigration policy and educational subsidies on the workers' decisions to invest in education and the entrepreneurs' decisions to adopt a new technology.[2] A key result is that a commitment to immigration of high-skilled workers is sufficient to ensure new technology adoption.

As in the work of Helpman and Rangel (1999), we distinguish between two forms of investment in human capital: (a) investment in general education[3] and (b) investment in technology-specific human capital. A worker's investment in technology-specific human capital depends on the time he spends in working in that technology. Since a worker can acquire technology-specific human capital by working in a particular technology, the more time he allocates to general education, the less time he has for accumulation of technology-specific human capital. We assume that each worker lives for two periods. In the first period, he decides how much to invest in education and how much in technology-specific human capital. In the second period, the output of the worker depends on the level of his first period investments in education and technology-specific human capital and on the type of entrepreneur with whom the worker is matched. We assume that matching between workers and entrepreneurs is random and anonymous.[4]

The entrepreneurs can be of two types: those who adopt the new technology in the second period and those who continue with the old technology. The new technology arrives only in the second period and the old technology refers to the technology from the first period. Due to the assumed random and anonymous matching between the workers and the entrepreneurs, a worker's decision to invest in human capital in the first period depends on his beliefs concerning the technology adoption decisions of the entrepreneurs in the second period. Since investment in education gives mobility to workers and increases returns from the new technology relative to the old one, workers will invest more in education when they expect more entrepreneurs to switch to the new technology in the second period.

[1] In explaining the East Asian 'miracle', Bhagwati (1996) observes that investments in new technologies and education created a 'virtuous cycle' which led to the sustained long-term growth in these economies.

[2] Both immigration policy and educational subsidies have been recently the focus of debate in some EU countries. Our analysis integrates these two public policy issues and shows how they are interrelated. Borjas (1994) considers the effect of immigration on the welfare of domestic workers, but not on their incentives to invest in education.

[3] Education in our model includes all education that improves managerial and/or technical knowledge of workers.

[4] Acemoglu (1997) also considers random matching and how it may influence investment in human capital. Bardhan and Udry (1999) show, using a simple variant of Acemoglu's model, that when labor markets are imperfect, underinvestment in human capital and a lack of technological innovation can be mutually reinforcing.

On the other hand, since higher level of investment in education by workers increases returns from the new technology relative to the old one, entrepreneurs may indeed adopt the new technology when the workers invest more in education. Conversely, if more entrepreneurs are expected to stay with the old technology, workers may devote more time in acquiring technology-specific human capital and less to education as that would increase their expected returns from the old technology relative to the new one. The consequent low investment in education may indeed lead the entrepreneurs to decide not to switch to the new technology. Hence, the technology adoption decisions of the entrepreneurs and the human capital investment decisions of the workers are interdependent.[5]

We obtain two types of equilibria in our model. A high-technology rational expectations equilibrium is obtained when workers expect all entrepreneurs to switch to the new technology and accordingly they invest sufficiently more in education. A low-technology equilibrium is obtained when the workers do not expect the entrepreneurs to switch to the new technology and thus invest less in education and more in technology-specific human capital.

A third type of equilibrium is also possible in which the entrepreneurs are indifferent between switching and not switching to the new technology. However, we rule out this type of equilibrium by introducing an additional behavioral assumption that an entrepreneur adopts the new technology whenever he is indifferent between the two technologies.

Due to the possibility of multiple rational expectation equilibria, the government may have a role in coordinating the expectations of the workers and the decisions of the entrepreneurs regarding the adoption of the new technology. We show that, through its policies, the government can indeed Pareto improve welfare. One particular policy we consider is commitment to immigration of educated or high-skilled workers. We show that if the government commits to such an immigration policy, then the local workers will also increase their investment in education and the economy will be lifted from the low-technology to the welfare improving high-technology equilibrium. We also discuss an alternative policy which is to subsidize education.[6]

Our paper differs from the existing literature in this area (e.g., Acemoglu, 1996; Redding, 1996) in at least two respects. First, there is a distinction between two forms of investment in human capital: investment in general education versus technology-specific human capital. Second, and most importantly, we explore the interaction between education and immigration policies which to the best of our knowledge has not been considered in the literature.

The paper is organized as follows. Section 2 presents the model. In Section 3, we characterize the optimization problems of the workers and the entrepreneurs. Section 4 proves the existence of the two types of equilibria. In Section 5, we analyze the welfare implications of education and immigration policies. Section 6 draws the conclusion.

[5] Redding (1996) extends Acemoglu's (1994) search framework and also proves the existence of multiple equilibria, the high and low innovative equilibria, where the high innovative equilibrium Pareto dominates the low one.

[6] Educational subsidies have been considered in the literature for raising investment in human capital, but that they may also be necessary for coordinating the expectations of workers and entrepreneurs has not been explored.

2. The basic model

As mentioned earlier, we consider a two-period model. Each period consists of a continuum of workers and entrepreneurs, each of measure one. Both workers and entrepreneurs live for two periods. The lifetime preferences of both workers and entrepreneurs are represented by the linear utility function[7]:

$$C_1 + \beta C_2, \tag{1}$$

where C_i denotes consumption in period $i=1$, 2 and $0<\beta<1$ is the discount rate.

2.1. The workers

We assume that each worker has an endowment of one unit of time in each period. Workers can use this endowment to acquire human capital in the first period. They can acquire two types of human capital, either: (a) invest in general education or (b) in technology-specific human capital (the effect of learning-by-doing in a particular technology). General education allows mobility across technologies in the second period and it is applicable to any technology. On the other hand, technology-specific knowledge is immobile and can only be applied to the specific technology. General education is costly as a worker needs to invest his time to acquire it, whereas technology-specific human capital is the learning-by-doing skills acquired on the job.

By considering two distinct types of human capital, we are able to introduce below a model of production in which returns from the new technology need not be higher compared to the old technology for all levels of investment in education by the workers. This is a key feature of our model.

We assume that workers make their decisions to invest in education in the first period before they enter the labor market. Let

$$L = 1 - v, \tag{2}$$

where v is the time spent on education. Then, L is the fraction of time spent working in the existing technology. By working in the existing technology in the first period, workers acquire technology-specific skills through learning-by-doing. Thus, young workers in the first period become skilled in the second period and the level of skill depends on the amount of time spent working in the technology in the first period.

2.2. The entrepreneurs

We assume that, like workers, the entrepreneurs are also ex-ante identical. The new technology arrives at the beginning of the second period and can be adopted only in that period. The entrepreneurs have the option of adopting the new technology or staying put with the existing one. Each entrepreneur employs one worker to produce the output.

[7] The assumption of linear utility function simplifies the analysis as it rules out intertemporal substitution in consumption.

2.3. The output

The production function for the first period is defined as:

$$Y^1 = AL = A(1 - v), \tag{3}$$

that is, the first period output depends on the amount of labor employed and on the productivity of the current technology, $A>1$.

In the second period, the output of an entrepreneur who stays put with the old technology is given by

$$Y_S^2 = A(B(1 - v) + av^{\theta}). \tag{4}$$

The term $B(1 - v)(= BL)$ captures the learning-by-doing effect or the returns from the investment in technology-specific human capital. Similarly, the term av^{θ} captures the returns from investment in education. For this reason, we shall sometimes refer to B and a as the returns to technology-specific human capital and education, respectively.

Since a worker lives for only two periods, he will not invest in education in the second period and will work full time in that period. Since $Y^1 = A$ and $Y_S^2 = AB$ when $v = 0$, we must have $B>1$, that is, the second period output must be higher as the worker has acquired technology-specific skills and works full time in the second period. Similarly, since $Y^1 = A$ when $L = 1$ and $Y_S^2 = Aa$ when $v = 1$, we must have $a>1$, that is, the second period output must be higher than the maximum first period output as the worker has invested in education and works full time in the second period. In fact, we assume that $\theta a>B>1$ and $0<\theta<1$, as these conditions are both necessary and sufficient to ensure (i) $\mathrm{d}Y_S^2/\mathrm{d}v = A(-B + \theta a v^{\theta-1})>0$ or all $v \in (0,1)$, that is, the second period output from old technology is increasing with investment in education, and (ii) $\mathrm{d}^2 Y_S^2/\mathrm{d}v^2 < 0$ that is, the marginal product of investment in education is declining.

If an entrepreneur adopts the new technology, then the second period output is given by

$$Y_A^2 = A^2 a v^{\theta}. \tag{5}$$

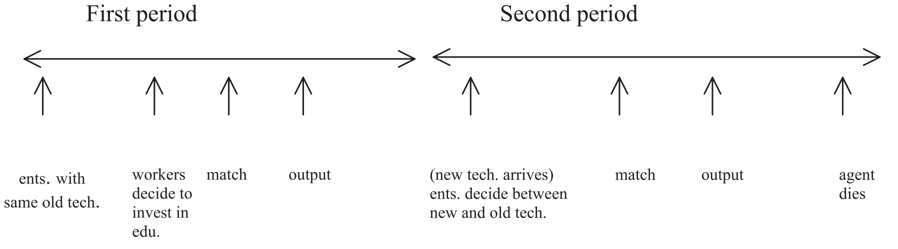
Unlike Eq. (4), the term $B(1 - v)$ is missing from Eq. (5) reflecting our assumption that technology-specific human capital is immobile and cannot be applied to the new technology. Furthermore, the parameter A(>1 by assumption) represents the productivity of the new technology.[8] Clearly, the second period output from the new technology is lower than from the old technology for low levels of investment in education, that is, $A(B(1 - v) + av^{\theta})>A^2 a v^{\theta}$ for sufficiently small v.[9] Furthermore, like Y_S^2, Y_A^2 is strictly increasing and concave in v.

[8] We could have adopted an alternative definition, namely, $Y_A^2 = CA_{av}^{\theta}$, where $C>1$ represents the productivity of the new technology. But except for adding an additional constant in the calculations below, this does not affect our analysis.

[9] The following results are not affected if we assume more general production functions. The specific forms assumed here, however, enable us to keep the analysis transparent.

2.4. Random matching

We assume that workers and entrepreneurs are randomly matched one to one in each period after they enter the labor market so that no worker or entrepreneur is unemployed.[10]



Workers decide to invest in education in the first period before they enter the labor market. In view of random matching, workers' decisions to invest in education are based on their beliefs regarding the technology adoption decisions of the entrepreneurs in the next period. At the beginning of the second period, the entrepreneurs decide whether to adopt the new technology based on the level of investment in education made by the workers in the first period. After the entrepreneurs technology adoption decisions, workers and entrepreneurs are again randomly matched one to one.

As in the work of Acemoglu (1994), we assume that the surplus created in each period from a match is divided between the entrepreneurs and the workers in fixed proportions. A worker who is matched with entrepreneur i, produces output Y_i and obtains $W_i = \alpha Y_i$ as his income. The entrepreneur gets $E_i = (1-\alpha)Y_i$ as his profit. The parameter α may be interpreted as the relative bargaining strength of the workers.

3. The decision problems

3.1. The entrepreneurs' decisions

Each entrepreneur maximizes his lifetime utility taking as given the educational investment decisions of the workers. Let E denote this utility. Then

$$E = [(1-\alpha)Y^1 + \beta \max\{(1-\alpha)Y_A^2, (1-\alpha)Y_S^2\}]. \tag{6}$$

We can rewrite Eq. (6) as

$$E = (1-\alpha)[A(1-v) + \beta \max\{A(B(1-v) + av^{\theta}), A^2 av^{\theta}\}]. \tag{7}$$

The decisions to adopt the new technology by the entrepreneurs depend on the relative returns from the two technologies in the second period which in turn depend on the level

[10] This means that there is a 100% separation at the end of the first period. The following analysis is not affected if we assume the separation rate to be less than 100%.

of investment in education made by the workers in the first period. An entrepreneur will be indifferent between the two technologies if

$$B = (A - 1)av^{\theta} + Bv. \tag{8}$$

Since $A>1, B, a>0$ and $0<\theta<1$, the expression on the right of Eq. (8) is strictly increasing, strictly concave, and strictly greater than B for $v=1$ Let v^* be the solution to Eq. (8), that is, the level of investment in education that makes the entrepreneurs indifferent between the old and new technologies. Then, $0<v^*<1$ as shown in Fig. 1 and the entrepreneurs will adopt the new technology if and only if the level of investment in education v is at least v^*.

This means that for low levels of investment in education, the entrepreneurs will stay put with the old technology, but for higher levels of investment in education, the entrepreneurs will adopt the new technology. As stated earlier, this is a key feature of our model that drives our results. If returns from the new technology were higher for all levels of investment in education, then the entrepreneurs will always adopt the new technology and the workers will not face any uncertainty regarding the technology in the second period.

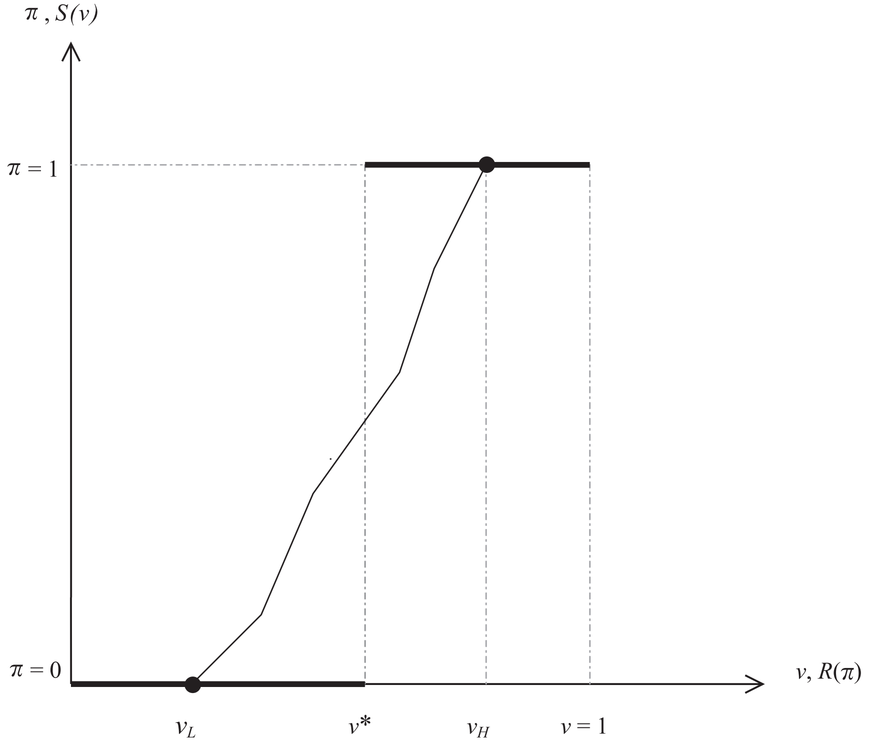


Fig. 1. High- and Low-Technology Equilibria.

3.2. The workers' decisions

In the first period, a worker decides to invest in education so as to maximize his lifetime (expected) utility

$$W = \alpha Y^1 + \beta((1-\pi)\alpha Y_S^2 + \pi\alpha Y_A^2), \tag{9}$$

where αY^1 is the income he earns in the first period, αY_S^2 is the income he will earn in the second period if he is matched with an entrepreneur who does not adopt the new technology, the probability of which is $(1-\pi)$, and αY_A^2 is the income he will earn if he is matched with an entrepreneurs who adopts the new technology, the probability of which is π. Since investment in education occurs before workers enter the labor market in the second period, the decision to invest in education is based on the fraction of the entrepreneurs, π expected to switch to the new technology. After substituting from Eqs. (3)–(5) and rearranging the terms, we can rewrite Eq. (9) as

$$W = \alpha[A(1-v) + \beta((1-\pi)AB(1-v) + aA((1-\pi)+\pi A)v^{\theta}). \tag{10}$$

Using the first order conditions for optimization and rearranging the terms, a worker's utility maximizing level of investment in education is given by

$$v(\pi) = \left(\frac{\beta\theta a(\pi A + (1-\pi))}{(1+\beta(1-\pi)B)}\right)^{\frac{1}{1-\theta}}. \tag{11}$$

It is easily seen that W is strictly concave in v and the second order condition for a maximum is satisfied. Since $A>1$ and $0<\theta<1$, $v(\pi)$ is strictly increasing with π. Therefore, the highest value that v can attain is when $\pi=1$. Substituting $\pi=1$ in Eq. (11), it is seen that the optimal level of investment in education by a worker in this case is

$$v_H = (\beta\theta Aa)^{\frac{1}{1-\theta}}. \tag{12}$$

Thus, if we assume $\beta\theta Aa<1$, that is, $\beta\theta$ is sufficiently small, then we obtain an interior solution for all values of π, and in order to avoid boundary problems, we assume henceforth that this condition indeed holds. Note that the level of investment in education is independent of B, the returns to technology-specific human capital.

For $\pi=0$, that is, when the workers expect none of the entrepreneurs to adopt the new technology, the optimal level of investment in education is the lowest and equal to

$$v_L = \left(\frac{\beta\theta a}{1+\beta B}\right)^{\frac{1}{1-\theta}}. \tag{13}$$

Note that in this case, the level of investment in education is independent of the productivity parameter A.

There is one more value of π which is of special interest. This is when $v(\pi) = v^*$. We do not explicitly solve for it, but note from Eq. (11) that such a π must be unique. Let π^* denote this value, that is, $v(\pi^*) = v^*$.

4. The equilibria

Since both workers and entrepreneurs make their investment decisions before they enter the labor market in the second period, our assumption of random matching in the labor market means that the identity of one's production partner is unknown and ex ante contracts that make one party's investment decision contingent on the other's are not possible. Moreover, since each worker and each entrepreneur act individually and independently, agents are unable to make their decisions sequentially. Given this background, the interdependence between the investment decisions of the two types of agents may result in multiple equilibria. We employ the pure strategy Nash equilibrium solution concept to solve for these rational expectations equilibria. In a rational expectations equilibrium, the workers beliefs regarding the adoption of the new technology induce the workers to invest in education at a level that is sufficient to induce the entrepreneurs to adopt the new technology in accordance with those beliefs. Since all workers are identical, each worker's level of investment in education is the same in a rational expectations equilibrium. We show that there exist three kinds of rational expectation equilibria.

Proposition 1. *There exists a rational expectation equilibrium, which must be one of the following three types: $\pi = 0$ and $v_L < v^*$; $\pi = 1$ and $v_H > v^*$; and $\pi = \pi^*$ and $v(\pi^*) = v^*$, where v^*, v_L and v_H are as defined above.*

Proof. We first prove existence. If $v_H > v^*$, then $(\pi = 1,\ v = v_H)$ is a rational expectation equilibrium, since workers' investments in education are sufficiently high to induce all entrepreneurs to adopt the new technology confirming the expectations of the workers.. If $v_H \leq v^*$, then $v_L < v^*$ since as shown earlier $v_L < v_H$. In this case $(\pi = 0,\ v = v_L)$ is a rational expectation equilibrium, since the workers' investments in education are so low that indeed no entrepreneur adopts the new technology confirming the expectations of the workers.

We have exhausted all the possibilities and shown that a rational expectation equilibrium exists in each of the cases. This proves existence. □

The arguments above not only prove the existence of a rational expectation equilibrium, but also demonstrate the possibility of the first two types of equilibrium. We now exhibit the possibility of the third type of equilibrium. In fact, it can arise in several different ways: (i) $v_L = v^*$, in which case $(\pi = 0,\ v = v_L)$ is a rational expectation equilibrium as the entrepreneurs, being indifferent between the two technologies, may indeed all stay with the old technology; (ii) $v_H = v^*$, in which case $(\pi = 1,\ v = v_H)$ is a rational expectation equilibrium as the entrepreneurs, being indifferent between the two technologies, may indeed all adopt the new technology; and (iii) $v_L < v^* < v_H$, in which case there exists a $\pi^* \in (0,1)$ such that $(\pi = \pi^*,\ v = v^*)$is a rational expectation equilibrium as an exact fraction

π^* of the entrepreneurs, all of whom are indifferent between the two technologies, may indeed adopt the new technology.

As seen from our existence proof, all three types of rational expectation equilibria are possible. The first type of rational expectation equilibrium arises when the workers expect no entrepreneur to adopt the new technology. In this case, the following condition must hold:

$$v_L = \left(\frac{\theta\beta a}{1+\beta B}\right)^{\frac{1}{1-\theta}} < v^*, \tag{14}$$

that is, the workers' investment in education is so low that no entrepreneur adopts the new technology. From the definitions of v^* (Eq. (8)) and v_L (Eq. (13)), which show that $v^*(v_L)$ is increasing (decreasing) with B, it is seen that a sufficient condition for this type of equilibrium to exist is

$$B\left[1-\left[\frac{\beta\theta a}{1+\beta B}\right]^{\frac{1}{1-\theta}}\right] > (A-1)a\left[\frac{\beta\theta a}{1+\beta B}\right]^{\frac{\theta}{1-\theta}}. \tag{15}$$

This inequality is satisfied if B is large and A is close to 1, that is, if returns from investment in technology-specific human capital are high and productivity of the new technology is low. In this equilibrium, workers have strong incentives to continue to work in the old technology and not to invest enough in education. The entrepreneurs therefore do not adopt the new technology.[11] We shall, therefore, refer to this type of equilibrium as the 'low-technology' equilibrium.

The second type of rational expectation equilibrium arises if

$$v_H = (\beta\theta aA)^{\frac{1}{1-\theta}} > v^*, \tag{16}$$

where, by assumption, $\beta\theta aA < 1$. From the definitions of v^* (see Eq. (8)) and v_H (see Eq. (12)), which show that $v^*(v_H)$ is decreasing (increasing) with A, it is seen that a sufficient condition for this type of equilibrium to exist is

$$(A-1)a(\beta\theta aA)^{\frac{\theta}{1-\theta}} > B(1-(\beta\theta aA)^{\frac{1}{1-\theta}}). \tag{17}$$

This inequality is satisfied if B is close to 1 and A is sufficiently large, that is, if the returns from investment in technology-specific human capital are low and the productivity of the new technology is high. We therefore refer to this type of equilibrium as the 'high-technology' equilibrium.[12]

[11] Economies in this equilibrium are characterized by a strong traditional sector which is able to pay high wages that act as a disincentive for workers to invest in education.

[12] This means that workers in economies characterized by low wages in the traditional sector are likely to invest more in education if they expect adoption of new technologies. The East Asian 'miracle' may be explained in these terms. Typically low wages in the traditional sector combined with the expectation of arrival of new technologies of relatively high productivity may have spurred these economies to this type of equilibrium.

For the existence of the third type of equilibrium, either Eq. (15) or Eq. (17) must hold with *equality* or both the inequalities. 15 and 17 must hold simultaneously. Since v^* solves Eq. (8), v^* is increasing with B and decreasing with A. Since v_L is decreasing with B, $v_L = v^*$ for a suitable value of B. Similarly, $v_H = v^*$ for a suitable value of A. Finally, as seen from Eqs. (8), (12) and (13), we can choose the values of B and A to be sufficiently large such that $v_H > v^* > v_L$. Since $v(\pi) = v_H$ for $\pi = 1$ and $v(\pi) = v_L$ for $\pi = 0$ and $v(\pi)$ is a continuous in π, it follows that there exists a π^* such that $v(\pi^*) = v^*$. This completes the Proof of Proposition 1.

Note that each type of equilibrium is unique because the expected utility function of each worker is strictly concave for each value of π fixed. We show below that an economy may have however more than one equilibrium, that is, more than one type of equilibria may coexist.

Equlibria of the third type require an exact fraction of the entrepreneurs to choose one of the technologies even though they are indifferent between them. Equilibria of this type are therefore unlikely to occur and are unstable. Even though such equilibria cannot be ruled out as a technical possibility, they are not of much interest[13] and we ignore them henceforth. Furthermore, these equilibria can be ruled out even as a technical possibility by making an additional behavioral assumption regarding the entrepreneurs which is that if an entrepreneur is indifferent between the new and old technologies then he adopts the new technology.[14]

Proposition 2. *The rational expectation equilibrium is not unique.*

Proof. Inequalities. (15) and (17) can be expressed jointly as

$$\frac{(\beta\theta a A)^{\frac{\theta}{1-\theta}}}{1-(\beta\theta a A)^{\frac{1}{1-\theta}}} > \frac{B}{a(A-1)} > \frac{\left(\dfrac{\beta\theta a}{1+\beta B}\right)^{\frac{\theta}{1-\theta}}}{1-\left(\dfrac{\beta\theta a}{1+\beta B}\right)^{\frac{1}{1-\theta}}}. \tag{18}$$

Notice that the expression on the left of this inequality is independent of the parameter B and the expression on the right is independent of A. Moreover, the expression on the left is increasing with A, whereas the expression on the right is decreasing with B. Therefore, by choosing sufficiently high A and B while keeping the ratio $B/(A-1)$ constant, we can find alternative solutions to inequality (18).

For example, let $A = 2$, $\theta = 1/2$, $\beta a = 1$. Since as noted earlier $\theta a > B > 1$, $\theta = 1/2$ and $\beta a = 1$, we must have $\beta B < 1/2$. Thus, take $a = 7/2$, $B = 3/2$, $\beta = 2/7$. It is easily seen that inequality (18) is satisfied. The same is true also for the alternative set of values $A = 5/2$, $\theta = 1/2$, $\beta a = 1/2$, $a = 5$, $B = 9/4$, $\beta = 1/10$. This proves Proposition 2. □

[13] As pointed out by an anonymous referee, however, this type of equilibria may explain the empirical fact that both new and old technologies may coexist.

[14] This is analogous to the assumption often made in the incentive literature (see, e.g. Chander, 1993) that if an agent is indifferent between misrepresenting preferences and telling the truth, then the agent tells the truth.

Proposition 2 shows that multiple equilibria may coexist for a wide range of values of the parameters. It also shows when the equilibrium may be unique and of which type: it is high-(low-) technology equilibrium if A and a are high (low) relative to B.

5. Government policies and economic welfare

The possibility of a low-technology rational expectations equilibrium leads us to consider government policies that can improve welfare. The government may either subsidize education or may raise through its policies the workers' expectations regarding the adoption of the new technology so as to increase their investment in education and attain the welfare improving high-technology equilibrium. We consider both types of policies. But first we prove the following.

Proposition 3. *The high-technology equilibrium Pareto dominates the low-technology equilibrium if the parameters a (i.e. the returns from investment in education) and A (i.e. the productivity of the new technology) are sufficiently high.*

Proof. Each worker's expected utility in the low-technology equilibrium is given by

$$W_{\mathrm{L}} = \alpha[A(1 - v_{\mathrm{L}}) + \beta A(B(1 - v_{\mathrm{L}}) + a v_{\mathrm{L}}^{\theta}] \tag{19}$$

and in the high-technology equilibrium by

$$W_{\mathrm{H}} = \alpha[A(1 - v_{\mathrm{H}}) + \beta A^2 a v_{\mathrm{H}}^{\theta}]. \tag{20}$$

Thus, the expected utility in the high-technology equilibrium is higher if

$$\beta B(1 - v_{\mathrm{L}}) + (v_{\mathrm{H}} - v_{\mathrm{L}}) < \beta a(A v_{\mathrm{H}}^{\theta} - v_{\mathrm{L}}^{\theta}). \tag{21}$$

which after substitution from Eqs. (12) and (13) can be rewritten as

$$(1-\theta)\theta^{\frac{\theta}{1-\theta}}(\beta a)^{\frac{1}{1-\theta}}\left[A^{\frac{1}{1-\theta}} - \left(\frac{1}{1+\beta B}\right)^{\frac{\theta}{1-\theta}}\right] > \beta B. \tag{22}$$

Clearly, this inequality is satisfied if both a and A are sufficiently high. Since output is shared in fixed proportions in each period among the workers and the entrepreneurs, the high-technology equilibrium Pareto dominates the low-technology equilibrium for sufficiently high values of a and A. □

5.1. Educational subsidies

Let s be the rate of educational subsidy. Then it is easily seen that a worker's optimal investment in education, if he does not expect the entrepreneurs to adopt the new technology (i.e. $\pi = 0$) is given by

$$v_s = \left(\frac{\beta\theta a}{1+\beta B - s}\right)^{\frac{1}{1-\theta}}. \tag{23}$$

Clearly, the educational subsidy has a positive impact on the level of investment in education by the workers. The level of subsidy required to shift the economy from the low- to the high-technology equilibrium can be calculated by substituting v_s in the above equation. By definition (Eq. (8)), v^* is an increasing function of the parameter B, whereas v_s is decreasing with B. It follows that the higher is B, that is, the higher is the return from investment in technology-specific human capital, the higher would be the subsidy required. Proposition 3 shows that the high-technology equilibrium may Pareto dominate the low-technology equilibrium. It may therefore seem that subsidizing education would Pareto improve the welfare. This intuition is however not entirely correct.

Note first that a worker's lifetime utility depends only on the amounts of outputs consumed and investment in education is not a consumption good, but an input in the production of the consumption good. Accordingly, it does not appear in the lifetime utility of the agents. Thus, the expenditure on educational subsidy is a direct resource cost and not a transfer to the workers.

Proposition 4. *Suppose the subsidy on education is financed through a uniform proportional income tax. Let the economy be currently in the low-technology equilibrium. Then the educational subsidy which is sufficient to shift the economy to the high-technology equilibrium may reduce welfare.*

Proof. Let s be the required rate of subsidy and let t be the uniform proportional income tax rate necessary for financing the subsidy. Then $tA(1-v^*)=sv^*$ and a worker's tax payment is equal to $t\alpha A(1-v^*)$ or αsv^*. Suppose contrary to the assertion that the subsidy is welfare improving. Then from Eqs. (19) and (20), we have

$$A(1-v^*)+\beta A^2a(v^*)^{\theta}-sv^*>A(1-v_{\mathrm{L}})+\beta(A(B(1-v_{\mathrm{L}})+av_{\mathrm{L}}^{\theta}). \tag{24}$$

This inequality follows from the fact that a worker's lifetime utility in the high-technology equilibrium when his investment in education is v^* minus his tax payment, αsv^*, must be higher than his lifetime utility in the low-technology equilibrium if the subsidy is welfare improving. This inequality can be rewritten as

$$\beta B(1-v_{\mathrm{L}})+v_{\mathrm{H}}-v_{\mathrm{L}}<\beta a(A(v^*)^{\theta}-v_{\mathrm{L}}^{\theta})+v_{\mathrm{H}}-v^*-\frac{sv^*}{A}. \tag{25}$$

This inequality is harder to satisfy than inequality (21) which is a necessary condition for welfare to be higher in the high-technology equilibrium. In particular, suppose $v^*=v_{\mathrm{H}}$ and Eq. (21)/Eq. (22) holds with equality, then Eq. (25) will clearly hold in the reverse. Since the expressions in the inequality. (21)/inequality. (22) are continuous, Eq. (25) will hold in the reverse even if Eq. (21)/Eq. (22) is strict. This proves that the educational subsidy may reduce welfare even when the high-technology equilibrium Pareto dominates the low-technology equilibrium.

Furthermore, if the workers' expectations change with the announcement of subsidy and they anticipate that all entrepreneurs will switch to the new technology, then the workers' investment in education will indeed be equal to v_{H} and not v^*. Therefore, by the argument just presented, the educational subsidy may reduce welfare. This completes the proof. □

It should however be noted that the above proposition only shows that the educational subsidy will reduce welfare when the gains from the high-technology equilibrium are small. It comes directly from the fact that the expenditure on educational subsidy is a direct resource cost and not a transfer to the workers.

5.2. The immigration policy

We now consider an alternative policy in that the government may commit to a credible immigration policy in the first period which allows the entrepreneurs to employ high-skilled workers from abroad in the second period if such workers are not available in the domestic labor market.[15] We assume that there exists a large pool of such workers available internationally.[16] Commitment to such a policy will have a positive impact on the incentives of the entrepreneurs and all of them will switch to the new technology in the second period. This in turn should change the expectations of the domestic workers regarding the adoption of the new technology from $\pi = 0$ to $\pi = 1$ and thus induce them to increase their investment in education from v_L to v_H thereby eliminating the actual need for high-skill immigrants. Unlike the educational subsidy, there is no resource cost or welfare loss associated with commitment to such an immigration policy.

6. Concluding remarks

Our paper analyses the interdependence between technology adoption and investment in education and its effect on welfare. Our analysis suggests that commitment to immigration of high-skilled is sufficient to shift the economy from the low-technology to the welfare improving high-technology equilibrium, as it induces the entrepreneurs to adopt the new technology and the workers to invest more in education. The result that such a commitment may eliminate the need for actual immigration is a consequence of our simplifying assumption that the economy has a single production sector. In general, there may be several production sectors with a new technology for each, which require different levels of skills. In such a case, commitment to high-skill immigration may reduce but not eliminate the need for high-skill immigrants and an educational subsidy may be needed to reduce it further. A lower educational subsidy may mean a higher demand for high-skill immigrants as the local workers would invest less in education. This means that there exists a trade-off between educational subsidies and the level of immigration.

The case for this trade-off is reinforced further by the findings in the literature on fiscal implications of immigration. For example, Storesletten (2000) reports that admitting

[15] More specifically, the entrepreneurs will have the option to employ high-skilled immigrants after the matching has occurred in the second period. Such an immigration policy is in fact practiced in the US with a well-defined procedure for verifying that no similarly educated local worker is available.

[16] This simplifying assumption enables us to assume that the distribution parameter α is exogenous. If the pool of such workers is limited, α may rise with adoption of the new technology and thereby reduce the incentive of the entrepreneurs to adopt the new technology but increase the incentive of the workers to invest in education.

young high-skilled immigrants represents a net fiscal gain to the host county, so that with a substantial immigration, the income tax rates can be reduced. Proportional (or progressive) income taxes discourage education (a negative s), and a tax cut is therefore effectively an increased incentive to pursue education (a less negative s). Thus, admitting high-skilled immigrants will actually stimulate investment in education through two different channels—the technology adoption channel emphasized here and through a lowering of income taxes.

Our static analysis can be extended to a dynamic model with non-overlapping generations in which the productivity parameter at time t is given by Ae^{bt}, where b denotes the (exogenous) rate of innovation. Accordingly, Eq. (8) is modified as $B=(Ae^{bt}-1)av^{\theta}+Bv$. Let $v^*(t)$ denote the solution to this equation. Then the economy will be in a low-technology equilibrium at time t if

$$v_{\mathrm{L}} = \left(\frac{\beta\theta a}{1+\beta B}\right)^{\frac{1}{1-\theta}} < v^*(t). \tag{26}$$

This is so because as in the static model v_{L} is independent of the productivity parameter and an entrepreneur's optimization problem is similar. As compared to the static model, however, the educational level that makes the entrepreneurs to switch to the new technology is lower and decreasing overtime, since $Ae^{bt}>A$. This means that innovation of new technologies over time with higher and higher productivity may induce the entrepreneurs at some point to switch to the new technology and a high-technology equilibrium may come to prevail on its own.

The strong economic growth in the US during the 1990s seems to be consistent with our analysis. The immigration reforms[17] introduced in 1990 may have been responsible for the subsequent higher investment in education. As seen from the U.S. Census Bureau data , while the number of citizens with only high school education fell in each age group, the number of citizens with college education rose rapidly during the 1990s which indicates a shift in favor of higher education. This and the fact that there was also rapid adoption and implementation of new technologies during the 1990s seem to confirm our analysis.

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[17] The 1990 Immigration Act changed the composition of employment immigrants who could be admitted to the US. The annual quota for immigrants based on employment was raised from 54,000 in 1991 to 110,000 in 1992. In addition, the act allowed for a larger quota for skilled immigrants as compared to unskilled. Prior to 1990s, only 27,000 visas were allowed for skilled immigrants and another 27,000 for unskilled. However, from the beginning of 1992, nearly 110,000 visas were allowed for skilled immigrants as compared to only 10,000 for unskilled (Statistical Yearbook of Immigration and Naturalization Service, 1998).

References

Acemoglu, D., 1994. Search in the labor market: incomplete contracts and growth. M.I.T. Working Paper no. 94-23. Cambridge, MA.

Acemoglu, D., 1996. A microfoundation for social increasing returns in human capital accumulation. Quarterly Journal of Economics 111, 779–804.

Acemoglu, D., 1997. Training and innovation in an imperfect labor market. Review of Economic Studies 64, 445–464.

Bardhan, P., Udry, C., 1999. Development Microeconomics. Oxford Univ. Press, United Kingdom. Chapter 12.

Bartel, A., Lichtenberg, F., 1987. The comparative advantage of educated workers in implementing new technologies. Review of Economics and Statistics 69, 1–11.

Bhagwati, J., 1996. The miracle that did happen: understanding East Asia in comparative perspective. Paper Presented at the Conference on Government and Market: The Relevance of the Taiwanese Performance to Development Theory and Policy. Cornell University. 38 pp.

Borjas, G.J., 1994. The economics of immigration. Journal of Economic Literature 32, 1667–1717.

Chander, P., 1993. Dynamic procedures and incentives in public good economies. Econometrica 61, 1341–1354.

Goldin, C., Katz, L., 1996. Technology, skill, and the wage structure: insights from the past. American Economic Review 86, 252–257.

Helpman, E., Rangel, A., 1999. Adjusting to a new technology: experience and training. Journal of Economic Growth 4, 359–383.

Krusell, P., Ohanian, L.E., Rios-Rull, J.-V., Violante, G.L., 2000. Capital–skill complementarity and inequality: a macroeconomic analysis. Econometrica 68, 1029–1053.

Redding, S., 1996. The low-skill, low-quality trap: strategic complementarities between human capital and R&D. Economic Journal 106, 458–470.

Storesletten, K., 2000. Sustaining fiscal policy through immigration. Journal of Political Economy 108, 300–323.