Technology adoption in a community of heterogeneous education level: Who are your good neighbors?

Yusuke Ono
University of Tokyo

Abstract

This paper examines the role of education in technology adoption in a multi-agent finite-time dynamic game setting. It is assumed that education decreases prior variance on the best action in using a new technology in the target-input Bayesian model, experience accumulates in a community (social learning; information spillover), and the experience, however, is not transferrable from one technology to another. The paper shows that, depending on the schooling distribution, the equilibrium creates different dynamic patterns of technology adoption.

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1. Introduction

In this study, we focus on a community where people with different levels of education decide whether or not to adopt new technologies. We mean two things by the word of community. First, everyone faces the same environment in terms of using technologies. Second, members in a community can observe the other member's activities and learn how to use the technologies; in other words, information is somewhat shared. A member's adoption of a technology therefore has influence on the other members' decisions.[1] Highly educated people are supposed to be able to guess well how to handle technologies.

Under these presuppositions, the improvement of the education level for some members in a community may have influence on the technology adoption behaviors in the whole community and the output level of the other members. These effects may be regarded as externalities of education. In our model, different kinds of externalities of education on output are found. They include negative externalities as well as positive ones. Our model shows that those whose education level is low are likely to undergo negative externalities.

In this paper, we use the target-input model which considers the effects of learning-by-doing and learning from others. In this respect, our model is similar to the model of Foster and Rosenzweig(1995) though the setting is unlike in some regards.[2] Since our interests are the influence of the neighbors' education level, we formulate the role of education in the context of the target-input model, partly following the way of Rosenzweig(1995).

Jovanovic and Nyarko(1996) also examines learning-by-doing and the choice of technology in the framework of the target-input model. However, the presuppositions of our model are different from those of theirs in some ways. For example, we assume that agents dynamically optimize their output whereas agents are myopic in the model of Jovanovic and Nyarko(1996). Further, education is not formulated in Jovanovic and Nyarko(1996).

This paper consists of four sections and appendixes. In the next section, our theoretical model is formulated. According to the model, technology adoption in a community of heterogeneous education level is explored in section 3. The analysis shows externalities of education on output. The last section concludes the paper. All formal proofs are shown in appendix A. The social optimality of an equilibrium is discussed in appendix B.

[1] Bardhan and Udry(1999) calls this "the externality generated by social learning".

[2] For example, we consider a menu of technologies as Jovanovic and Nyarko(1996) does.

2. Model

Setting Economic agents are engaged in production activities in a community. They are risk-neutral. They produce $q_{nt}(z)$, using technology $n \in \{0, 1, \ldots\}$ with input z in period t where $q_{nt}(z) = \gamma^n[1 - (y_{nt} - z)^2]$. The framework on which we are based is the target-input model.[3] γ is a real value which is bigger than 1. The value of γ is known. y_{nt} is the optimal level of input for technology n in period t where $y_{nt} = \theta_n + w_{nt}$. w_{nt} is distributed as a normal random variable with mean 0 and variance $\sigma_w^2 < 1$. w_{nt} is independent over agents and periods. The distribution of w_{nt} is known and common to all the agents in the community. The agents have priors over θ_n that are normal distributions with mean μ_0 and variance σ_0^2. $\sigma_0^2 = 1/e$ where e is the agent's education level, which is a positive real value. The agents' optimal choice for z is $\hat{z}_{nt} = E_t(y_{nt}) = E_t(\theta_n)$.

$$E_t(q_{nt}(\hat{z}_{nt})) = \gamma^n[1 - var_t(\theta_n) - \sigma_w^2].$$

In this setting, we examine a game with two players. The players are named i and j. Their education levels are denoted by e_i and e_j. The game begins with an adoption of a technology. Suppose that the level of this initial technology is 0. After that, the game proceeds as follows:

(1) Each player produces with the *ex ante* optimal input level, $\hat{z}_{nt}$. Suppose that each player can know the input and output levels of all the players after their production. Hence they know the true levels of optimal input and use the information to update their beliefs about all the technologies used in their production.

(2) They decide simultaneously whether they adopt a new technology or not. Adoption of a new technology increases the technology level by 1. Each player knows the other player's choice after their decisions.

(3) The step (1) and (2) are repeated once more.

(4) The step (1) is done again.

In this game, the players determine the adoption of a new technology twice. Their objective is to maximize the discounted sum of expected output of production for the three periods. In the first period, they begin to produce with the initial technology. After the first production, they decide whether or not to adopt a new technology. In the second period, they produce with the technologies selected by the decisions of the first period. After this second production, their second decisions about technologies for the production of the third period are done. We assume that the players act on a subgame perfect Nash equilibrium composed of pure strategies.

[3]The production function in our model is the same as the one in Jovanovic and Nyarko(1996) except that the latter allows n to take real values.

Skills In our production function, the expected outcome with $\hat{z}_{nt}$ is $\gamma^n[1 - var_t(\theta_n) - \sigma_w^2]$. This value decreases with $var_t(\theta_n)$. Hence $var_t(\theta_n)$ reflects the skills for using technology n.

$$var_t(\theta_n) = \frac{1}{e + x_{nt}/\sigma_w^2}$$

where x_{nt} is the cumulative number of times prior to period t that technology n is used for production.

In the setting of our model, people can learn how to use a technology if they use it or if their neighbors do. All experience of using a technology is socially experienced in the respect that information obtained by the experience is shared by all the members. We assume that experience is not transferrable from one technology to another. x_{nt} reflects the accumulation of the social experience of using technology n in the community up to period t. Individual skills for a technology are improved by the social experience of using it. In fact, $var_t(\theta_n)$ decreases with x_{nt}.

In our model, education is a source of the skills, too. For all n and t, $var_t(\theta_n)$ decreases with e. Whereas x_{nt} is beneficial only for technology n, education is useful for all the technologies. Literacy education is a good illustration of this. Literate people can take advantage of documented information. Besides, they can build a general framework for using technologies since the experience of reading many books may accustom them to thinking in a theoretic manner. Thus literacy may be effective in using even the technologies which are not used before.

In the framework of the target-input model, two advantages of education are formulated by Rosenzweig(1995). The first one is the improvement of access to information sources and the second one is that of the ability to decipher new information. Our model follows Rosenzweig's formulation about the first one. On the other hand, the second one is not formulated in our model. It follows from this supposition that we consider the situation where it is easy to interpret information obtained through production activities.

In our production function, the expected marginal value of education is

$$\frac{\gamma^n}{(e + x_{nt}/\sigma_w^2)^2}.$$

This declines with x_{nt}; in other words, education is more valuable when the technology is new to the community. It is evident that x_{nt} counts more when e is small; that is, the social experience of using a technology is more important to less educated people. x_{nt} and e are supposed to be substitutes in our framework.[4]

[4] On the other hand, schooling and experience may be complements in the framework of Rosenzweig(1995). The complementarity in the context of heterogeneous worker-firm matching

Education Level and Technology Adoption Let $r(n, x, e)$ denote the function of $\gamma^n(1 - \frac{1}{e+x/\sigma_w^2} - \sigma_w^2)$. An agent of education level e produces output level $r(n, x, e)$ when the agent uses technology n with the accumulation of the social experience x. As for $y > z$, we define $e(y, z)$ as the real value which satisfies both $r(n, y, e(y, z)) = r(n + 1, z, e(y, z))$ and $e(y, z) > -z/\sigma_w^2$. Although n is used for the definition, $e(y, z)$ does not depend on n.[5] $r(n + 1, z, e)$ increases more rapidly with e than $r(n, y, e)$ does. Hence, if $e > e(y, z)$, $r(n + 1, z, e)$ is bigger than $r(n, y, e)$ and if $-z/\sigma_w^2 < e < e(y, z)$, $r(n+1, z, e)$ is less than $r(n, y, e)$. Evidently, $e(y, z)$ is increasing with y and decreasing with z.[6]

In our model, the more educated are more likely to adopt a new technology. This is due to the assumption of the initial advantage of education in reducing prior variance σ_0^2; our specification is $\sigma_0^2 = \frac{1}{e}$. If we assumed that the more educated were able to obtain more information from each use of the technology, highly educated people might stick to the old technology because of its advantage of accumulated information. Whether or not the more educated are more likely to adopt a new technology would depend on the balance between the initial advantage and the learning advantage of education.

We assume that e_i and e_j are less than $e(2, 0)$. When both the players choose their technologies at the first period, they have already produced with the initial

is discussed in Yamauchi(2004). The complementarity is a plausible and interesting feature. Nevertheless, we assume that schooling and experience are not complements but substitutes. The reasons are as follows: First, assuming substitutability gives us clear and vital implications in our model. Under substitutability between schooling and experience, experience is more important to lowly educated people than highly educated people. Therefore lowly educated people are likely to be damaged when they lose their experience accumulated in the initial technology. Our discussions in this paper are based on this intuition. Second, the assumption makes our model simple and computationally tractable. In our setting, education level affects only initial prior variance σ_0^2 in a simple way. Third, assuming substitutability rather than complimentarity is reasonable under some situations. For example, if the decipher of information obtained through experience is easy enough, not assuming complimentarity is valid.

[5]Dividing $r(n, y, e(y, z)) = r(n + 1, z, e(y, z))$ by $\gamma^n > 0$, we get

$$1 - \frac{1}{e(y,z) + y/\sigma_\omega^2} - \sigma_\omega^2 = \gamma(1 - \frac{1}{e(y,z) + z/\sigma_\omega^2} - \sigma_\omega^2).$$

[6]Define $r_x(n, x, e) \equiv \frac{\partial r(n,x,e)}{\partial x} > 0$ and $r_e(n, x, e) \equiv \frac{\partial r(n,x,e)}{\partial e} > 0$. Since $y > z$,

$$r_e(n, y, e(y, z)) < r_e(n + 1, z, e(y, z)).$$

Hence

$$\frac{\partial e(y,z)}{\partial y} = \frac{r_x(n, y, e)}{r_e(n + 1, z, e) - r_e(n, y, e)} > 0$$

and

$$\frac{\partial e(y,z)}{\partial z} = \frac{-r_x(n + 1, z, e)}{r_e(n + 1, z, e) - r_e(n, y, e)} < 0.$$

technology. Hence x_{02} is equal to 2. The players have to produce with no accumulation of the social experience if they adopt a new technology; that is, x_{12} equal to 0. Hence, the initial technology is desirable for those whose education level is less than $e(2, 0)$. If they were myopic, they would never adopt a new technology at the first period. In our model, however, the players are assumed to optimize their payoffs dynamically.

Let k_i and k_j denote players' first decisions where 1 means adoption, 0 no adoption. Let (k_i, k_j) denote a subgame which starts at the second period after the players' first decisions k_i and k_j. There are four subgames, $(0, 0)$, $(1, 0)$, $(0, 1)$ and $(1, 1)$. The players' second choices are functions from the set of the subgames to $\{0, 1\}$. We call the functions l_i and l_j.

The dynamics of the social experience x_{nt} are specified as follows:

$$\begin{aligned} x_{01} = 0, \quad x_{02} &= 2, \quad x_{03} = 4 - k_i - k_j \\ x_{12} &= 0, \quad x_{13} = k_i + k_j \\ & \qquad\;\; x_{23} = 0. \end{aligned}$$

Let m_i and m_j denote technology levels for the third production;

$$m_i = k_i + l_i(k_i, k_j)$$

and

$$m_j = k_j + l_j(k_i, k_j).$$

The objective functions of the players are

$$v_i(k_i, l_i; k_j, e_i) \equiv r(0, x_{01}, e_i) + \delta r(k_i, x_{k_i 2}, e_i) + \delta^2 r(m_i, x_{m_i 3}, e_i)$$

and

$$v_j(k_j, l_j; k_i, e_j) \equiv r(0, x_{01}, e_j) + \delta r(k_j, x_{k_j 2}, e_j) + \delta^2 r(m_j, x_{m_j 3}, e_j)$$

where δ is the players' discount rate.

At the second period, player i's second choice $l_i(k_i, k_j)$ is determined in such a way to maximize player i's third production $r(m_i, x_{m_i 3}, e_i)$ where $m_i = k_i + l_i(k_i, k_j)$. This decision making depends on x_{03}, x_{13} and x_{23}, which are determined by k_i and k_j. Hence, k_i and k_j dictate $l_i(k_i, k_j)$ through the accumulation of the social experience, x_{n3}. Player i's first production $r(0, x_{01}, e_i)$ is not affected neither k_i nor k_j and player i's second production $r(k_i, x_{k_i 2}, e_i)$ does not depend on k_j. It is therefore the existence of the third period that makes decision making dynamic and strategic.

We solve the game by backward induction. We define $l_i^*(k_i, k_j)$ as player i's second choice which maximizes player i's third production given (k_i, k_j). It is meant by $l_i^*(k_i, k_j) = 1$ that player i should adopt a new technology at the subgame (k_i, k_j). Player i should adopt a new technology if

$$r(k_i, x_{k_i 3}, e_i) < r(k_i + 1, x_{k_i+1,3}, e_i).$$

Hence $l_i^*(k_i, k_j) = 1$ if $e_i > e(x_{k_i 3}, x_{k_i+1,3})$. For example, if $(k_i, k_j) = (1, 0)$, $x_{k_i 3} = x_{13} = 1$ and $x_{k_i+1,3} = x_{23} = 0$. Therefore $l_i^*(1, 0) = 1$ if $e_i > e(1, 0)$. If $(k_i, k_j) = (0, 1)$, $x_{k_i 3} = x_{03} = 3$ and $x_{k_i+1,3} = x_{13} = 1$, and therefore $l_i^*(0, 1) = 1$ if $e_i > e(3, 1)$. If $(k_i, k_j) = (0, 0)$, $x_{k_i 3} = x_{03} = 4$ and $x_{k_i+1,3} = x_{13} = 0$. If $(k_i, k_j) = (1, 1)$, $x_{k_i 3} = x_{13} = 2$ and $x_{k_i+1,3} = x_{23} = 0$. Since e_i is less than $e(2, 0)$, $l_i^*(0, 0) = l_i^*(1, 1) = 0$. Notice that l_i^* depends on e_i but does not on e_j. As for player j, $l_j^*(k_i, k_j) = 1$ if $e_j > e(x_{k_j 3}, x_{k_j+1,3})$.

There is a threshold value of the education level for the adoption at the first period. A player with education level more than e_k^* should adopt a new technology at the first period, given the other player's first decision $k \in \{0, 1\}$.[7] The lemma in appendix A shows the existence of e_k^*.

e_k^* depends on γ, σ_w^2 and δ. We provide a numerical example in this paragraph, assuming $\gamma = 1.04$, $\sigma_w^2 = 0.1$ and $\delta = 0.8$. Under this configuration, e_0^* satisfies[8]

$$r(1, 0, e_0^*) + \delta r(2, 0, e_0^*) = r(0, 2, e_0^*) + \delta r(0, 4, e_0^*).$$

e_1^* satisfies[9]

$$r(1, 0, e_1^*) + \delta r(1, 2, e_1^*) = r(0, 2, e_1^*) + \delta r(1, 1, e_1^*).$$

We obtain $e_0^* \approx 13.6721$ and $e_1^* \approx 13.6546$. Calculus teaches us that

$$\frac{\partial e_0^*}{\partial \delta} = -\frac{r(2, 0, e_0^*) - r(0, 4, e_0^*)}{r_e(1, 0, e_0^*) + \delta r_e(2, 0, e_0^*) - r_e(0, 2, e_0^*) - \delta r_e(0, 4, e_0^*)}$$

and

$$\frac{\partial e_1^*}{\partial \delta} = -\frac{r(1, 2, e_1^*) - r(1, 1, e_1^*)}{r_e(1, 0, e_1^*) + \delta r_e(1, 2, e_1^*) - r_e(0, 2, e_1^*) - \delta r_e(1, 1, e_1^*)}$$

where $r_e \equiv \frac{\partial r}{\partial e} = \frac{\gamma^n}{(e + x/\sigma_w^2)^2}$. The increase of δ implies that the future output counts more. Technology adoption in the first period increases the future output. Therefore the increase of δ makes technology adoption more advantageous and people more likely to adopt a new technology; that is, e_0^* and e_1^* decrease. $\frac{\partial e_0^*}{\partial \delta}$ is composed of two factors;

$$r(2, 0, e_0^*) - r(0, 4, e_0^*) \approx 0.0129616$$

[7] A Player's payoff is affected by the other player's first choice of the technology but is not by the second choice. Hence, the threshold value does not depend on the other player's second decision and therefore does not on the other player's schooling.

[8] See appendix A. $v_{10}^*(e_0^*) = v_{00}^*(e_0^*)$.

[9] See appendix A. $v_{11}^*(e_1^*) = v_{01}^*(e_1^*)$.

and

$$- \frac{1}{r_e(1,0,e_0^*) + \delta r_e(2,0,e_0^*) - r_e(0,2,e_0^*) - \delta r_e(0,4,e_0^*)} \approx -110.705.$$

The former is the future output increased by technology adoption. The increase of δ strengthens this advantage of technology adoption. The latter denotes how much e_0^* reacts to this intensified advantage of technology adoption. Similarly we can regard $\frac{\partial e_1^*}{\partial \delta}$ as the product of

$$r(1,2,e_1^*) - r(1,1,e_1^*) \approx 0.0130639$$

and

$$- \frac{1}{r_e(1,0,e_1^*) + \delta r_e(1,2,e_1^*) - r_e(0,2,e_1^*) - \delta r_e(1,1,e_1^*)} \approx -253.633.$$

We obtain $\frac{\partial e_0^*}{\partial \delta} \approx -1.43492$ and $\frac{\partial e_1^*}{\partial \delta} \approx -3.31345$; e_1^* moves more sensitively with the change of δ than e_0^* does. We can calculate $\frac{\partial e_k^*}{\partial \gamma}$ and $\frac{\partial e_k^*}{\partial \sigma_w^2}$ likewise.[10] The different sensitivities of e_0^* and e_1^* to the change of γ, σ_w^2 and δ lead to the two different cases, $e_0^* > e_1^*$ and $e_0^* < e_1^*$.[11]

[10]

$$\begin{aligned} \frac{\partial e_0^*}{\partial \gamma} &= -\frac{r_\gamma(1,0,e_0^*) + \delta r_\gamma(2,0,e_0^*) - r_\gamma(0,2,e_0^*) - \delta r_\gamma(0,4,e_0^*)}{r_e(1,0,e_0^*) + \delta r_e(2,0,e_0^*) - r_e(0,2,e_0^*) - \delta r_e(0,4,e_0^*)} \approx -243.856 \\ \frac{\partial e_1^*}{\partial \gamma} &= -\frac{r_\gamma(1,0,e_1^*) + \delta r_\gamma(1,2,e_1^*) - r_\gamma(0,2,e_1^*) - \delta r_\gamma(1,1,e_1^*)}{r_e(1,0,e_1^*) + \delta r_e(1,2,e_1^*) - r_e(0,2,e_1^*) - \delta r_e(1,1,e_1^*)} \approx -212.244 \end{aligned}$$

where $r_\gamma \equiv \frac{\partial r}{\partial \gamma} = n\gamma^{n-1}(1 - \frac{1}{e+x/\sigma_w^2} - \sigma_w^2)$,

$$\begin{aligned} \frac{\partial e_0^*}{\partial \sigma_w^2} &= -\frac{r_{\sigma_w^2}(1,0,e_0^*) + \delta r_{\sigma_w^2}(2,0,e_0^*) - r_{\sigma_w^2}(0,2,e_0^*) - \delta r_{\sigma_w^2}(0,4,e_0^*)}{r_e(1,0,e_0^*) + \delta r_e(2,0,e_0^*) - r_e(0,2,e_0^*) - \delta r_e(0,4,e_0^*)} \approx -20.1706 \\ \frac{\partial e_1^*}{\partial \sigma_w^2} &= -\frac{r_{\sigma_w^2}(1,0,e_1^*) + \delta r_{\sigma_w^2}(1,2,e_1^*) - r_{\sigma_w^2}(0,2,e_1^*) - \delta r_{\sigma_w^2}(1,1,e_1^*)}{r_e(1,0,e_1^*) + \delta r_e(1,2,e_1^*) - r_e(0,2,e_1^*) - \delta r_e(1,1,e_1^*)} \approx -35.0925 \end{aligned}$$

where $r_{\sigma_w^2} \equiv \frac{\partial r}{\partial \sigma_w^2} = -\gamma^n(\frac{x}{(\sigma_w^2)^2(e+x/\sigma_w^2)^2} + 1)$.

[11] Numerical examples are as follows:

e_0^*		e_1^*	γ	σ_w^2	δ
13.6721	$>$	13.6546	1.04	0.1	0.8
11.6463	$<$	11.8753	**1.05**	0.1	0.8
14.1244	$<$	14.4612	1.04	**0.08**	0.8
13.8266	$<$	13.9875	1.04	0.1	**0.7**

For example, this table shows that the increase of γ from 1.04 to 1.05 decreases e_0^* more than e_1^* and thereby e_0^* becomes less than e_1^*. The bold numbers in the table mean that they have changed from $\gamma = 1.04$, $\sigma_w^2 = 0.1$ and $\delta = 0.8$.

Whether $e_0^* > e_1^*$ or $e_0^* < e_1^*$ has some implications. For example, if $e_1^* > e_0^*$, there is e_i which satisfies $e_1^* > e_i > e_0^*$. At that time, player i should not adopt a new technology if player j does, and player i should do if player j does not; in other words, player j's adoption discourages player i's adoption.

The subgame perfect Nash equilibrium(SPNE) in our model is denoted by

$$(k_i^*, k_j^*, l_i^*, l_j^*)$$

where k_i^* maximizes $v_i(k_i, l_i^*; k_j^*, e_i)$ and k_j^* maximizes $v_j(k_j, l_j^*; k_i^*, e_j)$. Whether or not ($k_i^*$, k_j^*) constitutes a SPNE depends on the distribution of e_i and e_j. There is a SPNE with $k_i^* = 0$ and $k_j^* = 0$ if and only if $e_i \leq e_0^*$ and $e_j \leq e_0^*$, $k_i^* = 1$ and $k_j^* = 1$ if and only if $e_i \geq e_1^*$ and $e_j \geq e_1^*$, $k_i^* = 1$ and $k_j^* = 0$ if and only if $e_i \geq e_0^*$ and $e_j \leq e_1^*$, and $k_i^* = 0$ and $k_j^* = 1$ if and only if $e_i \leq e_1^*$ and $e_j \geq e_0^*$.

Patterns of Technology Adoption in a Community We can denote each player's history of technology adoption over two periods by natural numbers, $\{0, 1, 2, 3\}$. A number ω contained in this set has a dyadic expansion of $d_1(\omega)d_2(\omega)$. For instance, $d_1(2) = 1$ and $d_2(2) = 0$. If $d_t(\omega) = 1$, ω means that a technology was adopted at period t. For example, the natural number 1 means that technology adoption happened only at the second period since its dyadic expansion is 01. There are ten ways of technology adoption of two players over two periods.[12] We categorize them into the following four groups.

(1) Diffusion: If a player used the same level of technology as the other player had used before, it appears that the technology diffused among them. Hence we term this behavioral pattern *diffusion*. The player who had adopted first is called *leader*, and the other one who adopted later *follower*. The leader has to use new technologies with no social experience. On the other hand, the follower can utilize information obtained through the observation of the leader's using the technology. $\{1, 2\}$ and $\{1, 3\}$ belong to the diffusion.

(2) Separation: Another pattern of community's technology adoption is the *separation*, where a player adopted a new technology and the other did not any. The social experience of using a new technology is useless to the player who kept using the initial technology. $\{0, 1\}$, $\{0, 2\}$, $\{0, 3\}$ are classified as the separation.

(3) Unison: There is a case where both the players adopted the same level of technology at the same time. We call this case *unison*. When the two players use the same technology in unison, they can collect more information about the technology than they use it alone. $\{1, 1\}$, $\{2, 2\}$, $\{2, 3\}$, $\{3, 3\}$ are grouped into the unison.

[12]They are $\{0, 0\}$, $\{0, 1\}$, $\{0, 2\}$, $\{0, 3\}$, $\{1, 1\}$, $\{1, 2\}$, $\{1, 3\}$, $\{2, 2\}$, $\{2, 3\}$, $\{3, 3\}$.

(4) Deepening: If both the players do not adopt any new technologies, they can deepen their skills of using the initial technologies. Hence, we call this behavioral pattern *deepening*. Only $\{0, 0\}$ is the deepening.

3. How would your Neighbor's Education Level Affect you?

In this section, we show the effects of your neighbor's education level on your output level. There are player i and player j in our game. In this section, the effects of the rise of e_j on player i are examined. All the proofs for the propositions are given in appendix A.

Each member's education level has influence on his own behaviors of technology adoption. Each member's behaviors of technology adoption determine the community's accumulation of the social experience, on which each member's level of expected output depends. Hence, a member's higher level of education affects the other member's output level.

Positive Externalities by the Diffusion A member's higher level of education is likely to induce technology progress. The diffusion may accompany it and may be favorable to all.

Proposition 1 : *If* $e_i < \min\{e_0^*, e_1^*\}$ *and* $e(4,1) < e_i$, $e_j < e_0^*$ *implies the deepening and* $e_j > e_0^*$ *implies the diffusion where player i follows player j. Player i's expected outcome is higher in the latter than in the former.*

This proposition shows that the rise of e_j may work better off to player i holding e_i constant. When e_j is higher than e_0^*, it is better for player j to adopt a new technology at the first period if player i does not. Given player j's adoption of a new technology, it may be desirable for player i to delay the adoption so as to observe player j' using the technology. This is the pattern of the diffusion. Since player i can enjoy technological progress with observation on player j's production activities with a high level of technology , the output level of player i can be better than the deepening.

Negative Externalities by the Diffusion The diffusion does not always benefit all the members in the community. When the education level of the follower is low, the diffusion is not preferable to the deepening for the follower.

Proposition 2 : *If* $e_i < \min\{e_0^*, e_1^*\}$ *and* $e(3,1) < e_i < e(4,1)$, $e_j < e_0^*$ *implies the deepening and* $e_j > e_0^*$ *implies the diffusion where player i follows player j. Player i's expected outcome is lower in the latter than in the former.*

New technologies are used in the diffusion, and therefore less amount of the social experience is accumulated for the initial level of technology in the diffusion than in the deepening. The social experience counts more for less educated people. Hence less educated people prefer the deepening.

Negative Externalities by the Separation New technologies do not always diffuse. Those whose education level is very low keep using the initial technology alone even though the other members adopt new ones.

Proposition 3 : *If* $e_i < \min\{e_0^*, e_1^*\}$ *and* $e_i < e(3,1)$*,* $e_j < e_0^*$ *implies the deepening and* $e_j > e_0^*$ *implies the separation where player i does not adopt any new technologies. Player i's expected outcome is lower in the latter than in the former.*

In the diffusion, the follower adopts a new technology at the second period. If the follower's education level is low, however, it is better not to do. This is the case of the separation. At this time, lowly educated people are ought to keep using the initial one alone. Consequently, the accumulation of the social experience for the initial level of technology becomes less. Hence, the separation is less desirable to lowly educated people than the deepening.

Positive Externalities by the Unison If people in a community are all highly educated, they may adopt a new technology in unison at the first period.

Proposition 4 : *When* $e_i > \max\{e_0^*, e_1^*\}$*,* $e_j < e_1^*$ *implies the diffusion or the separation,* $e_j > e_1^*$ *implies the unison. Player i's expected outcome is higher in the latter than in the former.*

This proposition applies, for example, when those who are lowly educated get educated and the difference of education becomes narrower. Since $e_i > \max\{e_0^*, e_1^*\}$, player i adopts a new technology at the first period. When e_j is less than e_1^*, player j does not adopt a new technology at the first period. On the other hand, if e_j is more than e_1^*, all the players adopt a new technology together at the first period. Thereby the social experience for technology level 1 accumulates more. The advantage of the unison lies in this intensive accumulation of the social experience.

Who are Exposed to Negative Externalities? The discussions about the negative externalities by the diffusion and by the separation gives us the following corollary. The corollary shows that there are negative externalities from which only backward groups may suffer. Hence if the education level of members in a community is low, the policies which enhance the education level for only a part of members may be inappropriate.

Corollary: *Assume that* $e_i < \min\{e_0^*, e_1^*\}$*. If* $e_i < e(4,1)$*, player i is worse off when* $e_j > e_0^*$ *than when* $e_j < e_0^*$*. To the contrary, if* $e_i > e(4,1)$*, player i is better off when* $e_j > e_0^*$ *than when* $e_j < e_0^*$*.*

Those whose education level is low are likely to be exposed to negative externalities. Disadvantaged people tend to get worse because of the backwardness. This is an illustration of a vicious circle.

4. Conclusion

In this paper, we have examined the consequences of the rise of the neighbor's education level. We can summarize the results in terms of the difference in the education levels of the members in a community. The heterogeneity of the education levels may cause different behaviors of technology adoption between the members in a community.[13] When technologies are used heterogeneously, the accumulation of the social experience disperses over the various levels of technology, and thereby the amount of accumulation per technology becomes less. The social experience matters more to those whose education level is low, and therefore they are subjected to negative externalities by the wider gap in the education levels.

[13] The change from the deepening to the separation or the diffusion is an example.

Appendix A

Lemma for the existence of e_k^*

Lemma : There exists $e_k^* \in [0, e(2,0)]$ such that a player with education level more than e_k^* should adopt a new technology at the first period, given the other player's first decision $k \in \{0,1\}$ where 1 means adoption, 0 no adoption.

Proof: Define v_{00}^*, v_{10}^*, v_{01}^*, and v_{11}^* as follows:

$$\begin{aligned}
v_{00}^*(e) &\equiv r(0,0,e) + \delta r(0,2,e) + \delta^2 r(0,4,e) \\
v_{10}^*(e) &\equiv r(0,0,e) + \delta r(1,0,e) + \delta^2 \max\{r(1,1,e), r(2,0,e)\} \\
v_{01}^*(e) &\equiv r(0,0,e) + \delta r(0,2,e) + \delta^2 \max\{r(0,3,e), r(1,1,e)\} \\
v_{11}^*(e) &\equiv r(0,0,e) + \delta r(1,0,e) + \delta^2 r(1,2,e).
\end{aligned}$$

Notice that $v_i(k_i, l_i^*; k_j, e_i) = v_{k_ik_j}^*(e_i)$ and $v_j(k_j, l_j^*; k_i, e_j) = v_{k_jk_i}^*(e_j)$.

$v_{1k}^*(e)$ increases more with e than $v_{0k}^*(e)$. If $v_{1k}^*(e) = v_{0k}^*(e)$ at some real value between 0 and $e(2,0)$, the value is unique and suitable for the definition of e_k^*. If $v_{1k}^*(e) > v_{0k}^*(e)$ for e between 0 and $e(2,0)$, 0 is appropriate for the value of e_k^*. If $v_{1k}^*(e) > v_{0k}^*(e)$ for e between 0 and $e(2,0)$, $e(2,0)$ is appropriate for the value of e_k^*. We can therefore construct e_k^*. ■

Proofs for the Propositions

Notice that we use the notations, v_{00}^*, v_{10}^*, v_{01}^*, and v_{11}^* in the following proofs. They are defined in the proof of the lemma.

(1) Proof of proposition 1, 2, and 3

Assume $e_i < \min\{e_0^*, e_1^*\}$. Under this assumption, $k_i^* = 0$.

(a) $k_j^* = 0$ if $e_j < e_0^*$. Since $l_i^*(k_i^*, k_j^*) = l_j^*(k_i^*, k_j^*) = 0$, the technology adoption pattern on this SPNE is classified into the deepening. On this SPNE, Player i's payoff is $v_{00}^*(e_i)$.

(b) $k_j^* = 1$ if $e_j > e_0^*$.

If $e_i > e(3,1)$, $l_i^*(k_i^*, k_j^*) = 1$. The adoption pattern on this SPNE is the diffusion. Player i's payoff is $v_{01}^*(e_i)$. $v_{01}^* > v_{00}^*(e_i)$ if $e_i > e(4,1)$. On the other hand, $v_{01}^*(e_i) < v_{00}^*(e_i)$ if $e_i < e(4,1)$. Thus proposition 1 and 2 are proven.

If $e_i < e(3,1)$, $l_i^*(k_i^*, k_j^*) = 0$. The separation is the adoption pattern on this SPNE. Player i's payoff is $v_{01}^*(e_i)$. $v_{01}^*(e_i) < v_{00}^*(e_i)$ if $e_i < e(3,1)$. Thus proposition 3 is proven. ■

(2) Proof of proposition 4

Assume $e_i > \min\{e_0^*, e_1^*\}$. Under this assumption, $k_i^* = 1$.

(a) $k_j^* = 0$ if $e_j < e_1^*$. Player i's payoff is $v_{10}^*(e_i)$. If $e_j > e(3,1)$, $l_j^*(k_i^*, k_j^*) = 1$. The adoption pattern on this SPNE is the diffusion. If $e_j < e(3,1)$, $l_j^*(k_i^*, k_j^*) = 0$. The adoption pattern on this SPNE is the separation.

(b) $k_j^* = 1$ if $e_j > e_1^*$. The adoption pattern on this SPNE is the unison. Player i's payoff is $v_{11}^*(e_i)$. $v_{11}^*(e_i) > v_{10}^*(e_i)$ if $e_i < e(2,0)$. Thus proposition 4 is proven. ■

Appendix B

Social Optimality

In this appendix, we examine whether or not an equilibrium is social optimal. This appendix does not directly show the social optimal path given initial education levels but compare different cases. We show that the SPNE is not social optimal under certain configurations. We assume that e_k^* is neither 0 nor $e(2,0)$, and therefore e_0^* and e_1^* are defined as follows:

$$r(0,2,e_0^*) + \delta r(0,4,e_0^*) = r(1,0,e_0^*) + \delta \max\{r(1,1,e_0^*), r(2,0,e_0^*)\}$$

and

$$r(0,2,e_1^*) + \delta \max\{r(0,3,e_1^*), r(1,1,e_1^*)\} = r(1,0,e_1^*) + \delta r(1,2,e_1^*).$$

Inefficient Deepening If $e(4,1) < e_i < \min\{e_0^*, e_1^*\}$ and $e_j < e_0^*$, the deepening is an equilibrium whereas the diffusion is not. However, the deepening is inferior to the diffusion if e_j is near enough to e_0^*. Player i is better off in the diffusion than in the deepening. On the other hand, player j is worse off in the diffusion than in the deepening by

$$f(e_j) \equiv \delta r(0,2,e_j) + \delta^2 r(0,4,e_j) - \delta r(1,0,e_j) - \delta^2 \max\{r(1,1,e_j), r(2,0,e_j)\}.$$

$f(e_j)$ becomes less than player i's improvement if e_j is near enough to e_0^* because $f : R^{++} \to R$ is a continuous function and $f(e_0^*) = 0$.

Inefficient Diffusion If $e_i < \min\{e_0^*, e_1^*\}$ and $e(3,1) < e_i < e(4,1)$ and $e_j > e_0^*$, the diffusion is an equilibrium whereas the deepening is not. However, the diffusion is inferior to the deepening if e_j is near enough to e_0^*. Player i is better off in the deepening than in the diffusion. On the other hand, player j is worse off in the deepening than in the diffusion by $|f(e_j)|$. $|f(e_j)|$ becomes less than player i's improvement if e_j is near enough to e_0^*.

Inefficient Separation If $e_i < \min\{e_0^*, e_1^*\}$ and $e_i < e(3,1)$ and $e_j > e_0^*$, the separation is an equilibrium whereas the deepening is not. However, the separation is inferior to the deepening if e_j is near enough to e_0^*. Player i is better off in the deepening than in the separation. On the other hand, player j is worse off in the deepening than in the separation by $|f(e_j)|$. $|f(e_j)|$ becomes less than player i's improvement if e_j is near enough to e_0^*.

Another Inefficient Diffusion If $e_i > e_0^*$ and $e(3,1) < e_j < e_1^*$, the diffusion is an equilibrium whereas the unison is not. However, if e_j is near enough to e_1^*, the diffusion is less desirable than the unison. Player i is better off in the unison than in the deepening. On the other hand, player j is worse off in the unison than in the diffusion by

$$g(e_j) \equiv \delta r(0,2,e_j) + \delta^2 r(1,1,e_j) - \delta r(1,0,e_j) - \delta^2 r(1,2,e_j).$$

$g(e_j)$ becomes less than player i's improvement if e_j is near enough to e_1^* because $g : R^{++} \to R$ is a continuous function and $g(e_1^*) = 0$.

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