Chapter 12: Technological Progress and Learning

I

The process of economic development is characterized by a transformation of the technologies used in production. Technological change in the poor countries has often been seen as a process through which techniques of production invented and first used in the rich countries are imported and adapted for local use. Experimentation and learning have only a minor role to play in this process of technology transfer; production technologies are chosen “off the shelf” and are often embodied in capital goods imported from rich countries. The crucial determinants of this type of technological change are current and expected factor and product prices - poor countries need devote few resources to the process of invention itself.

If the changes in technology which occur as the currently poor countries develop are well-described by this notion of the transfer of technology, then this provides one of the “benefits of backwardness” described by Gerschenkron (1962). Poor countries can free ride on the investments in technology made in rich countries, and this might be one mechanism through which the convergence of productivity levels between poor and rich countries could occur.

It can be argued, however, that technological change in poor countries is more complex than a simple transfer of blueprints (or machines) from rich countries. Evenson and Westphal (1995) provide the useful vocabulary of “tacitness” and “circumstantial sensitivity” when characterizing technology. Techniques of production are tacit if they are not fully embodied in a set of artifacts - a collection of machines, seeds, manuals or blueprints, for example. The tacit elements of a technology might be employed quite differently across producers using ostensibly
identical techniques of production. Moreover, the performance characteristics of a particular
technique of production might sensitive to the circumstances under which it is used. Nontradable
inputs (most obviously, land) vary in characteristics in ways that affect the performance of
different technologies. The institutional context in which a technology is used (in particular, the
relationship between workers and managers) can also influence the performance of techniques of
production.

If a technology is characterized by tacitness or circumstantial sensitivity, then learning and
innovation are involved wherever it is newly applied - even if the explicit elements of the
technology are imported from a rich country. Thus tacitness and circumstantial sensitivity limit
the value of international spillovers, and require local investments in technology. This point
could be overemphasized - fundamental scientific advances remain a vital source of new potential
for the entire world. But the translation from abstract principles into new designs and then the
implementation of the new designs into production is not immediate or costless. It is locally
produced and adapted knowledge that provides a source of growth.

To overcome the tacitness or circumstantial sensitivity of a newly developed or imported
technology, there must be local investment in learning. Producers might engage in learning-by-
doing; experimenting with the new technology to reveal the tacit elements of the technology, or to
determine the sensitivity of the technology to local conditions. Alternatively, producers might
learn from others - either from other producers engaged in learning-by-doing, or from locally-
based researchers and extension agents.

The two types of learning have dramatically different implications for policy and for the
character of growth. When producers learn from their own experimentation, they undertake an
investment which yields uncertain returns. When producers learn from each other, not only is there a risky investment, but that investment generates an information spillover. This learning externality underlies some modern models of growth, and provides a role for government or other social institutions which might supply a mechanism for rewarding experimenters for the positive externality generated by their activities.

Taken together, these two types of learning form the process of “social learning”, in which knowledge generated by experimentation by an individual or firm increases that producer’s future profits and generates an information externality that benefits other individuals and firms. In section 2 of this chapter we present a simple model (after Foster and Rosenzweig, 1995) which provides a basis for thinking about the process of social learning, and which can serve as the foundation for a model of economic growth with endogenous technological change. In section 3, we link the process of technological innovation to investment in human capital, and show (using a simple variant of Acemoglu (1997)) that when labor markets are imperfect, under investment in human capital and lack of technological innovation can be mutually reinforcing.

II

We consider a very simple form of learning about a technology, which might correspond to a situation in which the parameters of a new technology (perhaps a seed) depend upon local conditions (perhaps soil characteristics) which vary across the world. This “target input” model (Prescott, 1972; Wilson, 1975; Jovanovic and Nyarko, 1994) has the characteristic that the basic form of the technology is known with certainty. Only a random parameter (known as the “target”) remains unknown. The profit of a producer declines with (the square of) the distance
between the input used and the unknown target level of input use. After the input has been applied and output realized, the producer can deduce what the target level of the input must have been. Each application of the technology, therefore, is an experiment which yields information about the distribution of the unknown random parameter. Producers learn by doing, gaining information about the production function through their own experimentation. They may also learn from others, observing the experiments of their neighbors and drawing lessons about the distribution of the target input level.

This model has been employed profitably by Foster and Rosenzweig (1995) in their study of farmers’ experimentation with Green Revolution seeds in India. This section presents a simplified version of their model, and retains the terminology of innovation in agriculture. The core ideas of social learning, however, are applicable to innovation more generally.

Suppose output is determined by the production function

$$q_{it} = 1 - (k_{it} - \kappa_i)^2,$$

where $k_i$ is the level of input use chosen by person $i$ in period $t$, and $\kappa_i$ is the target level of input use. $\kappa_i$ is not known at the time inputs are chosen. It is determined by

$$\kappa_{it} = \kappa^* + \mu_{it},$$

where $\mu_i$ is a normally distributed iid shock with mean zero and variance $\sigma_u^2$. At time $t$, person $i$ does not know $\kappa^*$, but she has beliefs about $\kappa^*$ which are distributed $N(\kappa^*, \sigma_{\kappa^*}^2)$. “Learning”, in this model, is a process of gathering information which permits the individual to make a better and
better estimate of the true value of $\kappa^*$. 

profits. This assumption doesn’t affect our discussion of the process of learning itself, but it does 

Maximization of expected profit implies that $k(t) = \kappa_t$. Therefore, 

$$E_t(q_{it}) = 1 - \sigma_{kit}^2 - \sigma_u^2.$$  \hfill (3) 

Expected profit rises as $\kappa$ declines; that is, as the individual learns more about the true value of $\kappa^*$.

Learning-by-doing

) and observes

output $(q_{it})$ $\kappa$ $\kappa^*$

and applying Bayes’ rule to update her beliefs about $\kappa$, 

$$\sigma_{kit}^2 = \frac{1}{\sigma_{kat^2} + \frac{1}{\sigma^2}}.$$ 

Defining $\frac{1}{\sigma_u} = \mu$ 

\hfill 1For the sake of simplicity we assume (rather unrealistically) that the farmer knows that the variance of $\mu = \sigma_u$. \hfill
and \( \frac{1}{\sigma_{ki0}^2} = \rho_{i0} \) as the precision of i’s initial beliefs about the value of \( \kappa^* \), (4) becomes

\[
\sigma_{kit}^2 = \frac{1}{\rho_{i0} + I_{t-1} \rho},
\]

(4’)

where \( I_{t-1} \) is the number of trials of the new technology that i has observed on her own farm from period 0 through \( t-1 \). So we can write expected profits as a function of the number of trials:

\[
Eq(I_{t-1}) = 1 \cdot \frac{1}{\rho_{i0} + I_{t-1} \rho} - \sigma_{u}^2.
\]

(3’)

Additional experiments with the new technology increase future expected profits:

\[
\frac{\partial Eq(I_{t-1})}{\partial I_{t-1}} = \frac{\rho_o}{(\rho_{i0} + I_{t-1} \rho)^2}.
\]

(5)

Eventually, as the farmer collects more and more information, she becomes certain about the value of \( \kappa^* \). Taking the limit of (4’) as \( I \) increases, we have \( \lim_{I \to \infty} \sigma_{kit}^2 = 0 \) and \( \lim_{I \to \infty} Eq = 1 - \sigma_{u}^2 \).

B. Learning from Others.

Learning-by-doing can be a quite slow mechanism, particularly in agriculture where it is usually necessary to wait a season, and often longer to observe the outcome of an experiment. The process of learning would be much faster if information from neighboring farmers could also be used. If neighboring farmers share the same technology, in the sense that the distribution of
the unknown target input level is the same, then they might be able to learn from each other. In agriculture in particular, the distance over which farmers can usefully learn from each other might be quite limited (that is, some types of agricultural technology might be quite highly sensitive to local circumstances such as soil characteristics and weather patterns). In the context of this model, it might be the case that the distribution of $\kappa_n$ is different in different localities, so that observations from one location about realizations of $\kappa_n$ in one place provide little information about its distribution in another.\(^2\) For now, though, consider neighboring farmers for whom the new technology has identical characteristics.

Suppose that farmer $i$ can observe, with some error, the input choice and yield of each farmer $j$ living in the same village. Thus $i$ observes $\kappa_{ji} + \epsilon_{ji}$, where $\epsilon_{ji} \sim N(0, \sigma_{\epsilon}^2).$\(^3\) In a richer model, one might permit the distribution of the noise in the information flow between farmers $i$ and $j$ to depend on their relationship. But we maintain the simpler model which ignores the subtler issues of social networks within the village. Defining $\rho = \frac{1}{\frac{1}{\sigma_{\kappa}^2} + \frac{1}{\sigma_{\epsilon}^2}} < \rho_o$, we have

\[
2 \kappa = \frac{1}{\rho + \rho_o \frac{N_{t-1} \rho}{I_{t-1}}}
\]

where $I_{t-1}$ is the number of trials of the new technology that $i$ has observed on all the farms of her

\(^2\)See Munshi (1995) for a discussion of social learning in this situation.

\(^3\)Again, suppose that $\sigma_{\epsilon}^2$ is known.
neighbors from period 0 through period t-1.

The externality generated by social learning is now apparent. If one farmer experiments with a new technology, this generates information for all his neighbors and increases their expected profits. Thus

\[
\frac{\partial E q_t(I_{t-1}, N_{t-1})}{\partial N_{t-1}} = \frac{\rho_v}{(\rho_{k0} + I_{t-1} \rho_o + N_{t-1} \rho_v)^2} > 0.
\]

(7)

A farmer’s decision to use and thus experiment with a new technology has implications for all of her neighbors, and thus the adoption of technology is a social process. Decisions about technology use, we will see in the next section, depend not only on a farmer’s evaluation of its profitability, but also on the nature of a farmer’s interactions with the other farmers in her neighborhood.

C. Adoption of Technology

Suppose that the farmers have available a “traditional” technology, the parameters of which are known with certainty. To simplify notation, we presume that the return from this technology is riskless and equal to \(q_o\), but nothing in what we say depends on this assumption. For the moment, abstract from social learning and presume that each farmer learns about the parameters of the new technology independently. Let \(\tau_i = 1\) if the farmer uses the new technology in period t and 0 if she uses the traditional technology. The value of the future stream of profits of farmer i from period t through period T is:
where \( I_s = \sum_{t=0}^{s} \tau_t \). Focusing on period \( t \):

\[
V_t(I_{t-1}) = \max_{\tau_t} \sum_{s=t}^{T} E_t \delta^{s-t} ((1 - \tau_s) \cdot q_a + \tau_s \cdot q_s(I_{s-1})),
\]

(8)

Two comments are in order. First, note that since expected profits are increasing in the number of trials of the new technology, once the farmer switches to the new technology she will continue to use the new technology forever. That is, since Eq. (I ) is strictly increasing in \( I_{t-1} \) (recall equation (5)) then if \( \tau_t = 1, \tau_s = 1 \) for all \( s > t \). This observation underscores an important weakness of the target input model as the basis of a model of technological change. The history of technology is replete with examples of innovations that are attempted and then abandoned once proven less profitable than alternative technologies. The target input model begins with the assumption that the new technology is superior; the problem of learning is concerned with discovering the precise shape of the new technology. An alternative approach (adopted, for example, by Besley and Case, 1996 and Ellison and Fudenberg, 1996) would be to focus on discovering whether or not a new technology is profitable in a particular environment.

Second, the switch from the old technology to the new may take place when the old technology is still more profitable. Consider a farmer in period 0 and her decision to adopt the new technology. She will adopt the new technology in period 0 if
\( q_a - E q(0) \leq \delta (V_1(1) - V_1(0)). \) \hspace{1cm} (10)

So if the loss in current expected profits is less than the (discounted) gain in future profitability from the additional trial of the new technology, the new technology will be adopted. The right hand side of (10) is positive:

\[
V_1(1) - V_1(0) = E_0 \sum_{s=1}^{T} \delta^s (q(s) - q(s-1)) = \sum_{s=1}^{T} \delta^s \left( \frac{1}{\rho_{i0} + (s-1)\rho_m} - \frac{1}{\rho_{i0} + s\rho_m} \right) > 0,
\]  

so the new technology may be used even if the current expected profit from the new technology is less than that which would be received from the old.

If farmers can learn from each others’ experience with the new technology, the choice of a farmer to adopt the new technology will depend crucially on the farmer’s interactions with everyone else in the village. The value of future profits to a farmer depends not only on her own experience with the new technology (\( I_t \)), but also on the experience of everyone else in the village (or other appropriately defined reference group) (\( N_t \)):

\[
V_t(I_{t-1}, N_{t-1}) = \text{Max}_{\tau_t} (1 - \tau_t) \cdot q_a + \tau_t \cdot E q_t(I_{t-1}, N_{t-1}) + \delta V_{t+1}(I_t, N_t). \]  

Hence a farmer’s expectations about his neighbor’s use of the new technology have a direct effect on the value of the flow of profits expected by that farmer. The more experimentation that she expects her neighbors to conduct, the higher the profit she expects. At the same time, a farmer who expects that many of her neighbors will adopt the new technology may delay her own adoption, because the value of the information that she will receive from experimenting with the
crop is lower the more other farmers experiment. To see this, note that our farmer will choose to use the new technology if

\[ q_a - E_0 q(0) \leq \delta (V_1(1,N_0) - V_1(0,N_0)). \]  

(13)

The right hand side is again positive, reflecting the increase in the flow of expected profits as a consequence of the information gained by the farmer experimenting with the new technology in period zero. However, the right hand side is declining in \( N_0 \) - if more other farmers use the new technology, less additional information is gained by the farmer experimenting herself. Thus, if many of your neighbors have characteristics that would lead them to adopt early, it might be in your interest to refrain from experimenting yourself.

The spread of technology, therefore, depends on social interactions in a number of ways. First, there is the direct effect of information flow within the community. People might be learning from each other’s experiments. It is likely that the extent of learning from others depends on the technology itself and on a host of characteristics of the community itself. An important program of empirical research, therefore, is to document the extent of “information spillovers” generated by experimentation. Second, there is the issue of the impact of the externality. Is there any social mechanism which serves to reward experimenters for the value of their experiments to other farmers? This, of course, is the primary justification for intellectual property rights protection, but it may be the case (particularly in the context of agricultural innovation) that there are a variety of less formal mechanisms which reward experimentation and innovation. Finally, the pattern of adoption of innovations depends on the nature of the game that is being played in the community. In the context of our model, each farmer is simultaneously faced with a problem
determined? Is it the simple Markov-perfect experimentation is not internalized by the farmer. Or are there enforcement mechanisms, multi-period punishments, or other institutional arrangements which make other equilibria possible?

Nyarko and Jovanovic (1994) address the issue of continuous technological progress. They model the problem of learning about an entire sequence of technologies indexed by $z=1, 2, \ldots$, 

$$
\gamma^z = \gamma^{i, z} \kappa
$$

provides some $\kappa$. Thus experimentation with technology $z$ not only generates information which makes the use of that technology more profitable (for both the experimenter and her neighbors), but it also makes further innovation more profitable.

part of innovators. Data from experimentation throughout a community is pooled (perhaps with some noise added as information flows from person to person), and the parameters of the activity in poor countries; for example with Amanor’s (1994) description of on-farm experimentation in Ghana. Other models of social learning, however, might be appropriate in (1993), who analyze how innovation would occur if producers used simple, exogenously specified rules of thumb to guide their adoption decisions. They focus on rules of thumb in which adoption relative popularity of the different techniques. They show that the success with which such naive
rules lead to the adoption of more efficient technologies depends crucially on the precise rule of thumb that it is in use, and on the nature of the technology itself (particularly the degree to which its profitability depends on local conditions).

The simple model presented in this section illustrates two important characteristics of innovation in the context of social learning. First, innovation is a form of investment. Producers engage in costly experimentation, sacrificing current profits in exchange for knowledge which will increase profits in the future. Second, innovation generates spillovers. This is the case because new technology, in the sense of designs or methods for doing a task, is non-rival. Use of a new technique by one person does not prevent another person from also using the same technique. Thus if one person learns about a new technology, others can benefit from that knowledge. It may be the case (depending on the technology and the social context) that this new knowledge is only partially (or not at all) excludable - it may not be possible to prevent others from observing your use of the new technology and thus benefitting from your experimentation. In this case, there is an externality generated by your investment.

III

Thus far, we have focused on the problem of learning - the locally produced and adapted knowledge that permits producers to change their techniques of production. However, even when all the characteristics of the new technology are known with certainty, adoption might not be a simple matter. The use of new technology often requires a different economic environment than use of the old. Changes in the institutional context of production (new contracts, or new ways of organizing labor), or in infrastructure, or in the skills of the labor force might be required.
It is on the last of these that we focus in this section. Potentially profitable new technology might not be used if the available workforce does not have the requisite skills. This notion is at the center of Rosenstein-Rodan's (1943) argument that “the first task of industrialization is to provide for training and 'skilling' of labour” (p. 204). Simultaneously, the return to human capital and hence workers' and firms' incentives to invest in training appears to be very sensitive to the rate of technological change in an economy. In a dynamic environment characterized by rapidly changing technology, the returns to education and training are exceptionally high.⁴

This interdependence between training and the adoption of technology need not be problematic. If the training is firm-specific, so that it is valuable only inside the firm providing the training, then the training will be provided and the technology adopted if the productivity gains outweigh the costs of the training and new technology. This is the efficient outcome. In the case where the skills imparted by training are generally useful, Becker (1964) shows that in a competitive labor market, firms providing the skills charge the employees the present discounted value of the increased wages these employees will be able to earn in the future as a consequence of their improved skills. A significant component of training in poor countries, as in rich countries, takes place in apprenticeship programs. Master mechanics, tailors, machine shop operators and the like provide the training to apprentices required to keep the informal sectors of many economies vibrant.⁵ Again, the skills will be provided and the technology adopted if and only if the productivity gains outweigh the costs of training and the new technology.

⁴Schultz (1975) forcefully states this argument, and Foster and Rosenzweig (1996) provide supporting evidence from the Indian green revolution.

⁵See, for example, Berry's (1985, chapter 6) rich description of motor mechanics in Ile-Ife, Nigeria.
When markets are imperfect, however, a lack of coordination can inhibit both training and innovation. For example, liquidity constraints could limit the ability of workers to pay for the general training they receive (see Velenchik (1995)), and this could in turn limit the profitability of adoption of a new technology. Rosenstein-Rodan (1943) focused on labor market imperfections - if workers are not paid their marginal products, then future employers might not have to pay trained workers for the full value of their training. In his words, “there are no mortgages on workers - an entrepreneur who invests in training workers may lose capital if these workers contract with another firm” (p. 204). When labor markets are imperfect, training can generate a positive externality to firms that will employ labor in the future. When this externality is not internalized, workers and firms will invest in suboptimal levels of training, and the profitability (and rate) of innovation may be too low. To formalize this argument, we present a simplified version of the model developed by Acemoglu (1997).

Suppose that there is an economy with a continuum of risk-neutral workers and risk-neutral firms, each with mass 1. The discount rate is r (perhaps this is a small open economy with access to international capital). The economy lasts for two periods. Each firm requires one worker to produce y units of output in each period. In period 1, it is possible to make two sorts of investment to increase productivity in period 2. First, a new technology might be adopted at cost $\delta$ to be used for production in period 2. Second, a worker can be provided with general training which will increase her productivity in any firm in the second period. $\tau$ units of training can be obtained at a cost of $c(\tau)$, where $c(.)$ is differentiable, strictly increasing and convex, and $c(0) = 0$. The crucial assumption about the technology is that training and the new technology are complementary. To sharpen the point, we will assume that this complementarity is very strong:
the new technology will not improve output unless used with a trained worker, and the training will not be useful unless used with the new technology. Define \( \gamma_j = 1 \) if firm \( j \) has invested in the new technology and \( \gamma_j = 0 \) otherwise. If worker \( i \) with training \( \tau_i \) is paired with firm \( j \) in the second period, then output is \( y + \gamma_j \alpha \tau_i \), where \( \alpha > 0 \). Output increases in the second period only if a firm with the new technology is matched with a worker who has been trained. Finally, there is an exogenous probability \( s \in (0,1) \) that a worker-firm pair in period one is forced to separate and match with a different partner in period two. In a frictionless labor market, this separation does not create any problem, because there is a continuum of firms which will be able to employ any worker forced to leave her period one firm.

In an efficient allocation, the surplus generated by training and technology adoption is maximized:

\[
\begin{align*}
\max_{\gamma \in \{0,1\}, \tau} \quad & \gamma \alpha \tau - (1 + r)(c(\tau) + \delta \gamma).
\end{align*}
\]  

The first term is the additional output generated by training and adoption of technology, and the second term is their cost (which is incurred in the first period). If \( \gamma = 0 \), the optimal level of training is obviously \( \tau^l = 0 \). If \( \gamma = 1 \), then the optimal level of training is \( \tau^h \) such that

\[
\alpha = (1 + r)c'(\tau^h).
\]  

If \( \delta > 0 \), it is clearly not profitable to innovate unless workers are trained. Suppose in addition that

\[
\alpha \tau^h - (1 + r)(c(\tau^h) + \delta) > 0,
\]  

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so that it is optimal to choose to adopt the technology and train the workers. Acemoglu (1997) shows that it is possible to support this efficient allocation in a competitive equilibrium. The intuition is simple. The wage for workers in the second period \( w \) working for firms which adopt the technology is a function of their level of training, such that \( w(\tau) - w(0) = \alpha \tau, \forall \tau \). In the first period, workers are paid a wage \( v(\tau) \) which depends on the training they receive. In the competitive equilibrium workers pay for their training, so \( v(\tau) = v(0) - c(\tau), \forall \tau \). If (16) holds, all workers chose \( \tau = \tau^h \) and all firms chose \( \gamma = 1 \).

Suppose, however, that there is an imperfect labor market. We will not model the imperfection explicitly, but suppose that firms are randomly matched with workers at the start of period 1. Given this match, they cannot switch before period 2 and hence they bargain over the division of the surplus in the relationship. At the end of period 1, a fraction \( s \) of the matches are dissolved and randomly matched with a new partner for period 2. Again, given this match, no more switches are possible, and the firm and workers again bargain over the division of the remaining surplus. Suppose that the bargaining process is such that the worker gets a fraction \( \beta \) of the surplus, while the firm gets \( (1-\beta) \). This generates the following externality. Suppose that a trained worker is separated from her firm and matched with a new firm for period 2. The new firm now captures a proportion of the value of the investment that has been made in training that worker. Hence, in the first period, firms and workers recognize that a third party might take some of the second period benefits of the training, and they underinvest in training.

First consider the simple case where we abstract from the adoption of technology. This will permit us to show the underinvestment in training result most clearly. Let \( \delta = 0 \) so that all firms adopt the new technology. At the start of period two, with probability \( s \), worker \( i \) is
separated from her initial employer. She negotiates a contract with her new employer and receives a wage of $\beta(Y + \alpha \tau)$. The firm and worker take account of the possibility of a separation in the first period training decision. The surplus generated for the firm and worker by training level $\tau$ is:

$$TS = \frac{1}{(1 + r)} \left[ (1 - s)(y + \alpha \tau) + s(\beta(y + \alpha \tau) + (1 - \beta)(y + \alpha \int \bar{\tau} dF(\bar{\tau}))) - c(\tau) \right].$$

(17)

The final term is the cost of training, which is realized in the first period. The first term is discounted, for it is the benefit of training, realized in the second period. The first component is simple, for it is the probability that the match continues into the second period, times the output given the continued match. The second component is the probability that the match is dissolved times the returns to the worker in that case, plus the returns to the firm in that case. The worker gets $\beta(y + \alpha \tau)$ from her new firm. The firm gets $(1 - \beta)$ of the output given its new worker.

$F(\bar{\tau})$ is the distribution function of training among workers, so $y + \alpha \int \bar{\tau} dF(\bar{\tau})$ is the firm's expected output in period 2, given the dissolution of the first period match. Choosing $\tau$ to maximize (17), we see that firms and workers will choose $\hat{\tau}$ such that

$$(1 + r)c'(\hat{\tau}) = (1 - s)\alpha + s\beta \alpha < \alpha,$$

(18)

so that $\hat{\tau} < \tau^h$. Despite the fact that all firms are assumed to have adopted the new technology, there is underinvestment in training. This is a consequence of the fact that in period two with probability $s$, only $\beta \alpha$ will be gained from the training, rather than $\alpha$. The other portion of the gain, $(1 - \beta)$, was captured by the firm lucky enough to have been matched with the trained worker.
in period two. Only if \( s=0 \), so that matches do not dissolve, or if \( \beta = 1 \), so that workers capture all the benefit of their training is this allocation efficient. The labor market imperfection, therefore, leads to underinvestment in training.

We now consider the way in which this market imperfection can interact with the choice to adopt new technology. Assume once more that \( \delta > 0 \) so that the technology is costly. However, maintain assumption (16), so that the technology (combined with optimal training) is socially valuable. Suppose that a proportion \( \phi \) of firms adopts the technology in the first period. A worker with training \( \tau \) who with probability \( s \) is forcibly separated from her firm has a second period expected wage of \( y + \phi \alpha \tau \). The firm and the worker at the start of period one choose \( \tau \) and \( \gamma \) (recall that \( \gamma \in \{0,1\} \) indicates adoption of the technology) to maximize their joint surplus, which is analogous to (17):

\[
\text{Max}_{\gamma \in \{0,1\}, \tau} \frac{(1-s)(y+\gamma \alpha \tau)}{(1+r)} + \frac{s[\beta(y+\phi \alpha \tau) + (1-\beta)(y+\gamma \alpha \int \bar{\tau} dF(\bar{\tau})] - (c(\tau) + \gamma \delta)}{(1+r)}.
\]  

We will now show that it is possible that this economy has two equilibria: one in which all firms adopt the new technology and all workers receive (suboptimal, but positive) training \( \hat{\tau} \), and the other in which no firms adopt the technology and no workers are trained. In the latter equilibrium, there is no incentive to train workers because no firms adopt the new technology, and no firms adopt the new technology because of the dearth of trained workers.

To see that the first equilibrium is possible, suppose that \( \phi = 1 \), and that all workers have training \( \hat{\tau} \) (so all of the mass of \( F(\bar{\tau}) \) has all of its mass at \( \hat{\tau} \)). Now consider a firm and worker
choosing $\gamma$ and $\tau$ to solve (19) with $\phi=1$ and $\int \hat{\tau} dF(\hat{\tau}) = \hat{\tau}$. If they chose $\gamma=1$, then they will also chose $\tau = \hat{\tau}$, because (18) describes the relevant first order condition. In the case of a separation, the second period wage of the worker is $\beta(y + \alpha \hat{\tau})$ (because $\phi=1$) and the second period earnings of the firm are $(1-\beta)(y + \alpha \hat{\tau})$ (because all workers get $\hat{\tau}$ training). So the gain from adopting the innovation and choosing training level $\hat{\tau}$ is $\alpha \hat{\tau} - (1+r)(\delta + c(\hat{\tau}))$.

Does anyone have an incentive to deviate from this possible equilibrium? Suppose a firm/employee pair decides not to innovate in the first period. What level of training would this pair choose? Training has no benefit if the pair remain together, but with probability $s$ the worker will be separated and matched with a firm with the new technology (recall that $\phi=1$), and in that event her wage will be $\beta(y + \alpha \tau)$. The cost of training remains $(1+r)c(\tau)$, so the deviating pair would chose $\tau = \bar{\tau}^l$ such that

$$(1 + r)c'(\bar{\tau}) = s\beta \alpha < (1 - s)\alpha + s\beta \alpha. \quad (20)$$

So $\bar{\tau}^l < \hat{\tau}$. The gain to a firm/worker pair of choosing $\gamma=0$ and $\tau = \bar{\tau}^l$ over choosing $\gamma=0$ and $\tau=0$ is $s\beta \alpha \bar{\tau}^l - (1+r)c(\bar{\tau})$ (the first term is the expected extra income earned as a consequence of the training, and the second term is the cost of training). Hence, if

$$\alpha \hat{\tau} - (1 + r)(\delta + c(\hat{\tau})) > s\beta \alpha \bar{\tau}^l - (1 + r)c(\bar{\tau}^l) > 0 \quad (21)$$

no firm/worker pair will have an incentive to deviate from the equilibrium in which every firm adopts the technology and every worker receives training $\hat{\tau}$. Note that (21) is more restrictive
than the assumption (16), but it is based on the same idea that the innovation/training combination is sufficiently profitable that it generates surplus.

The allocation in which no firm adopts the technology and no worker is trained is also an equilibrium. Suppose $\phi=0$ and no worker is trained (all the mass of $F(\bar{\tau})$ is at 0). If a firm/worker pair chooses not to adopt the technology, it will also chose zero training. There is no return from training if the pair stays together in the second period, nor (given $\phi=0$) is there any return to training if the pair is separated. Is there any incentive for this pair to deviate from this equilibrium? If they adopt the technology ($\gamma=1$), they chose a level of training $\tau = \bar{\tau}^h$ where

$$ (1 + r) c'(\bar{\tau}^h) = (1 - s) \alpha < (1 - s) \alpha + s \beta \alpha. \quad (22) $$

The lhs of (22) is the marginal cost of training. The rhs is the marginal gain from training, which is only realized if the pair remain together. So $\bar{\tau}^h < \bar{\tau}$. The gain to the pair from choosing to adopt the technology and train the worker is

$$ (1 - s) \alpha \bar{\tau}^h - (1 + r) (\delta + c(\bar{\tau}^h)) \quad (23) $$

where the first term is the additional output from training and adopting the technology, which is only realized if the match is not dissolved, and the second term is the cost of adoption plus training. If (23) is negative, then no firm/worker pair has an incentive to deviate from the equilibrium in which no firm adopts the technology and no worker is trained. Note that it is possible for (23) to be positive, in particular if $s$ is small enough. If the firm/worker pair is confident that they will not be separated, then any profitable technology will be adopted.
In this model, therefore, there can be two possible equilibria. These equilibria are Pareto ranked. In the high equilibrium, all firms adopt the technology and all workers are trained (to the level \( \hat{\tau} \)). Each pair generates a surplus equal to \( \alpha \hat{\tau} - (1+r)(\hat{\sigma}+c(\hat{\tau})) \), which by (21) is positive, and this surplus is split between the worker and the firm. The externality generated by the labor market imperfection leads to underinvestment in training (\( \hat{\tau} \) is less than the optimal \( \tau^b \)), but there is a sufficiently high level of training in the general workforce that firms are not inhibited from adopting the new technology. In the second equilibrium, there is no innovation nor is any worker trained. No surplus is generated, so both workers and firms are strictly worse off than in the first equilibrium. No single worker/firm pair has an incentive to deviate from this bad equilibrium. It is not worth paying for the technology and training the worker because of the probability that the pair will be dissolved. The separated worker would be paired with a firm which has not adopted the technology, so her skills would be useless. The separated firm would wind up with a worker unable to utilize the new technology.

This model has formalized the argument of Rosenstein-Rodan (1943) that investment in human capital, in the specific form of training workers, generates an externality when labor markets are imperfect. Combining this insight with the notion that training and the adoption of new technology are complementary leads to the possibility of multiple Pareto ranked equilibria. The model illustrates the possibility of an economy trapped in a poor equilibrium in which potentially profitable new technology is not adopted because of insufficient investment in the human capital of workers, and simultaneously low returns to investment in human capital because of the low rate of technological innovation. Moreover, it is impossible for an individual firm and its workers to profitably break out of this equilibrium due to the externalities generated by training.
in the context of imperfect labor markets.

In this chapter, we have examined two aspects of technological change in poor countries. The first is learning and experimentation. We have argued that technological transformation of production in poor countries generally involves more than a simple transfer of ideas and/or machines from rich countries. Most often, innovation is required in order to adopt the technology to the conditions in which it is to be used. This innovation involves experimentation and learning, both from producers' own experience and from the experience of similarly situated producers in the same economy. The spread of technology, therefore, commonly involves social learning.

Second, we have argued that even when the technology is well-understood, adoption of a new technology might require a different economic environment than continued use of an existing technology. In this chapter, we focused on the possibility that new technologies require a more highly-skilled labor force. This requirement, coupled with the existence of labor market imperfections, raised the possibility of an economy trapped, unable to adopt a new technology because of an inappropriately-trained labor force, and unable to provide appropriate training due to the existing technology of production.

**References**


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