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Technology Transfer through Movement of Labor among Firms

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I. Introduction

A growing literature analyzes technology transfer from multinational affiliates in developing countries to local firms. However, relatively little attention has been paid to analyzing the detailed mechanics such technology transfer, particularly through training of skilled labor in the multinational firm and its later movement to a local firm. Yet recent empirical studies find that in some developing countries FDI has little or no technological spillover to local firms (Aitken and Harrison 1999; Harrison 1996), and this suggests that it is time for such detailed analysis, to find what might prevent technology transfer. Harrison (1996) suggests that one cause for failure of technology transfer may be that multinationals pay higher wages to their skilled workers than do local firms (Aitken, Harrison and Lipsey 1996), so that, once trained, few of these workers ever return to local firms to transfer new technology. Glass and Saggi (1999) do, however, report some evidence of exceptions, for example in South Korea, where movement of managers and others from multinationals to local firms has played a significant role in transferring technology. The present paper contributes to filling a gap in the literature on technology transfer from multinationals to local firms in developing countries, by analyzing this process specifically as the training of skilled workers in the multinational firm and their subsequent movement to employment in local firms.

Glass and Saggi (1999) took an important first step in modeling this process by analyzing a static duopoly game in which technology may or may not be transferred from a multinational subsidiary to a local firm in a developing country through movement of workers. In that model, whether technology transfer occurs depends crucially on how completely skills can be transferred. First, suppose transferability of skills is high; that is, suppose that when multinational workers move to jobs in local firms they are nearly as productive there as in the multinational. Then local firms will optimally offer a wage close to the value of these workers' product in the multinational, and in that case it will be quite expensive for the multinational to retain their services by matching that wage. Under these conditions they found that multinationals are likely to yield to defection of these workers, and therefore to technology transfer. On the other hand, suppose skills are poorly transferable, and that a multinational worker's productivity after moving to a local firm is only a little higher than that of an untrained worker from the general labor pool. In this case, the highest wage bid that the local firm will make will be far below the value of these workers' marginal product in the multinational; so Glass and Saggi found that since the multinational can, with a relatively low wage offer, outbid the local firm, it is more likely to do so and to retain its workers, forestalling technology transfer.

Thus the outcome of the Glass-Saggi static game is that technology transfer may or may not occur, depending on the value of q, the quantity of labor a trained worker requires to produce a unit of output in the local firm, divided by the quantity of labor used by the same worker to produce a unit of output in the multinational. Technology transfer occurs when q is close to 1, so that technology is highly transferable, but when q is large, technology transfer is prevented by the source firm. Glass and Saggi show that for linear market demand the critical value of q is 2.[1] This means that when a worker who moves to the host firm is at least half as productive as she was in the multinational, the source firm allows the movement to occur, and technology transfer takes place. When the worker would be less than half as productive in the host firm, the source firm pays a high enough wage to discourage movement, and no technology transfer takes place.

Part of the motivation for the present paper is the intuition that while the static Glass-Saggi model seems reasonable as a first approximation, the outcomes in the model might be sensitive to apparently minor elements of the model specification. The model's outcomes may also be sensitive to the omission of some realistic features. For example, in the Glass-Saggi model, training is costless and instantaneous. Making training costly seems capable of substantially affecting how much technology transfer occurs.

To explore these issues, we look at a model with four features which seem likely to have a significant effect on the amount of technology transfer that occurs. First, there is more than one period, and in each new period a new and more productive vintage of technology may be adopted by the multinational firm; the host firm may adopt the newest vintage of technology available to it,, provided it can get trained workers to operate it, or may operate some earlier vintage, whichever it finds to be optimal. Second, training (assumed available only in the multinational firm) is a costly and time-consuming

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[1] In their model, as long as untrained workers are less productive than trained workers, then for linear demand their productivity level does not affect the critical value of q.

process, and it is cheaper to train workers who already have a high initial level of skill. Third, a worker's skill is only partially transferable from one vintage to the next. Fourth (as in the Glass-Saggi model), a skilled worker is less productive in the host firm than in the multinational firm, because complementary inputs such as expert advice from the multinational's headquarters are unavailable.

Section II presents the general features of the model, and then the solution for the one-period model and the solution for the two-period model. Section III discusses some issues about the functioning of the labor market and suggests directions for further research. Section IVconcludes.

II. The model

Two firms, a "source firm" (thought of as a multinational subsidiary in a developing country) and a "host firm" (locally owned), produce a homogeneous good and sell it in a market in which they are the only two producers. In each period the firms engage in strategic interaction in two different ways. First, at the beginning of each period in the game, each competes with the other to acquire the services of the most-skilled workers, in order both to reduce its own marginal cost and to increase its rival's marginal cost. Since only the source firm is able to provide training in the newest vintage of technology, the supply of most-trained workers is only large enough to supply the labor for one firm[2]. Hence in principle a firm may be able both to reduce its own marginal cost and to increase its rival's marginal cost in one blow, by hiring the most-trained workers and denying their services to its rival.

After a preliminary period (called period 0) in which the source firm trains a first group of workers, the sequence in each following period is this: the source firm makes a wage offer, and then the host firm makes a wage offer, and finally the source firm has the opportunity to make a counter-offer. The workers then accept the highest wage offer, and those who end up in the source firm may receive training in the newest vintage of technology. The source firm finds it optimal to provide such training. Finally, the two

[2] We proceed on the assumption that both firms have the same size labor force. However, this assumption is contrary to fact, since the choice of Cournot output will sometimes require a larger labor force in one firm than in the other. For the present we proceed with the analysis as if this were not a problem, in order to

firms choose output levels, competing as a Cournot duopoly and reaping payoffs in the form of profits. In period j, the source firm chooses whether to operate the newest vintage j, and if it does so, it always provides training in that vintage. We assume that training always raises all employees' skill level s to the highest possible level, namely $s = 1$.

The host firm either produces using a backward technology and a less-trained group of workers, or else successfully hires trained workers away from the multinational by offering them a wage which the multinational does not find it optimal to match. However, if the host firm does recruit these workers, it is still at a disadvantage, for two reasons. First, we assume technology is transferred imperfectly: in the host firm all the former multinational workers take q units of labor ($q > 1$) to produce a unit of output which in the source firm takes only 1 unit of labor to produce. Second, we assume that the host firm can only acquire new technology with a lag: workers must undergo a full period of training in the source firm in vintage $j - 1$, during period $j - 1$, before they may be hired away by the host firm to operate vintage $j - 1$ in period j (or later).

We define a worker's skill level in operating vintage j during a given period, at time t measured from the beginning of the period, as $s_j(t)$, with $0 \leq s_j(t) \leq 1$. It may be thought of as a percentage of best practice. (When we refer to the source firm, not only the vintage but also the period is j, while when we refer to a worker in the host firm, the period will be made clear in context.) Units are chosen so that each period is one unit of time in length. There is an initial period 0, in which workers in both firms are trained in vintage 0, but the firms do not interact strategically over wages; since both hire from the general labor pool of untrained workers, they both pay the reservation wage, defined by choice of units as $w = 1$. A worker who has never received any training is assumed to operate vintage 0 with initial low skill level $1/Q$, and we assume $q < Q$ so that a trained worker from the source firm always produces more in one period in the host firm (namely, $1/q$) than does an untrained worker. As long as a worker is employed in the host firm, her skill level in a given vintage remains unchanged period after period. If she is employed in the source firm, however, she receives training in the newest vintage in each period j in which it is provided, with her skill s_j always rising to 1 by the end of the

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get a first approximation and an overall approach to solution; later, once the entire game and its solution in the one-period and two-period case have been presented, we return to this point and clarify the issue.

period. This training is necessary upon upgrading to a new vintage, since we assume that only a fraction l of a worker's skill in vintage j carries over to the new vintage $j + 1$, with $0 < l < 1$. Hence a worker in the source firm for periods 0 and 1 starts period 1 with $s_1(0) = l$. A worker in the host firm who has never received training operates vintage 1 with $s_1(0) = l/Q$, and in general operates vintage j with skill $s_j(0)= l^j/Q$.

Thus l imposes a cost to upgrading in the form of lost output. However, there is also a benefit to upgrading, since we assume that each new vintage is more productive than the last by a factor of g, with $g > 1$. The instantaneous flow of output of a worker with skill level s_1 in vintage j will be $s_j g^j$, which is g^j times the output of that worker in vintage 0. We assume $lg < 1$ so that the source firm only finds it optimal to upgrade if it also provides training in the new vintage of technology.[3]

Output per worker in vintage j is defined as $\int_0^1 g^j s(t)dt$, so potential output, operating vintage j in a period, if it were possible to hire workers with skill $s_j = 1$, is g^j. It is convenient to define a function $C(s) = 1 - \int_0^1 s(t)dt$ which resembles a "cost-of-training" function, but is defined in skill units rather than output units and so does not take account of the greater productivity of newer vintages of technology. Hence the true cost of training expressed in lost output is $g^j C(s_j(0))$. (Below, the vintage j will often be assumed to be understood from the context, and suppressed from the skill level.)

The $C(s)$ function can have various possible shapes, corresponding to the shape of the learning curve $s(t)$. Minimum requirements for a $C(s)$ function are that the "cost" of training be smaller for workers with a higher initial skill level (C¢ < 0) and that workers who have already attained maximum skill require no training ($C(1) = 0$). Figure 1a shows a possible learning curve $s_j(t)$ that corresponds to a particularly simple $C(s)$ function, $C(s) = (1/2)(1 - s)$. Its shape might be justified by assuming that all the source firm workers go through the same training program in operating vintage j, lasting the full length of the period. While they all receive training at the same pace, those with a lower initial skill level get more out of the program than others (filling larger gaps in their knowledge), and by the end of the period they all have reached the same level $s = 1$.

Other learning curves could be drawn, for example, ones for which the cost of training rises more steeply as initial skill level declines.

In the source firm, output per worker using vintage j in period j will be denoted by $F[j, s_j(0)] = \int_0^1 g^j s_j(t)dt = g^j(1 - C(s_j(0)))$. Figure 1b shows the evolution of output per worker in the source firm as long as it retains its workers and upgrades and trains them in each period. For example, in period 1, a source firm worker retained from the previous period produces $F[1, l] = g(1 - C(l))$, so if $C(s) = (1/2)(1 - s)$, output per worker will be $g(1 + l)/2$. Notice that this may be greater or less than 1, so that in principle the source firm could produce less output by upgrading to vintage 1 than by continuing to operate vintage 0 using workers trained in the previous period. If period 1 were the last period of the game, upgrading would then not be optimal for the source firm (and if it were not the last period, it might be optimal or might not, depend on the consequences of the upgrading decision for the cost structure of future periods. To keep matters simple, in the very first part of the analysis we will assume that the parameters take on values for which it is never optimal for the source firm to skip an upgrade; shortly, this assumption will be relaxed.

A. The one-period model

We first solve what will be called the "one-period" game, with a preliminary period 0 in which both firms pay the reservation wage of unity, and workers in the source firm receive training, followed by period 1 in which the full game is played. The one-period game will illustrate the general method of solution, which we will then use to analyze the two-period game.

We assume that each firm has complete information about the structure of the game and hence can deduce the present and future decisions of its rival. If the source firm knows that its own maximal wage offer to retain its workers is higher than will be the maximal wage offer of the host firm to try to recruit them, then the wage it actually will pay will be the host firm's highest offer, plus an arbitrarily small e, and it will retain its workers. In that case, the host firm will pay the reservation wage $w = 1$ and hire from the

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[3] Figures 10-14 do not currently reflect this constraint, which would cut off more or less the upper right

general labor pool. Since in this case workers trained in period 0 remain in the source firm in period 1, no technology transfer will occur. On the other hand, if the source firm knows that the host firm is prepared to match and exceed its optimal highest wage offer, it will surrender the field in period 1 and pay the reservation wage, letting the first group of workers take their newly acquired skills and move to the host firm, and hiring another group of trainees from the general labor pool. In this case, technology transfer will occur and the host firm will pay the highest wage that the source firm would match, plus an arbitrarily small *e* which we will ignore.

At the beginning of period 1, those who worked in the source firm in period 0 now have $s_0 = 1$, while host firm workers still have $s_0 = 1/Q$. If the host firm's period-1 wage bid, which we will denote w_{HH1}, exceeds the source firm's, then each worker it hires will produce $1/q$ units of output, at a constant marginal cost of $w_{H1}q$. (The double-*H* subscript in w_{HH1} is meant to distinguish this hypothetical host firm maximal wage bid from w_{H1}, the wage the host firm actually ends up paying.) The source firm will then hire new, untrained workers at the reservation wage $w = 1$, and each will produce $F[1,1/Q]$ units of output at a constant marginal cost of $1/F[1,1/Q]$. If, on the other hand, the source firm's maximal wage bid w_{SS1} is higher, it will retain its workforce and train it in vintage 1. Then each worker will produce $F[1, l\,]$ units of output, and the marginal cost will be $w_{S1}/F[1, l\,]$. The host firm will continue to hire untrained workers at $w = 1$, each producing $1/Q$ units at a marginal cost of Q.[4]

These outcomes are summarized in Table 1; *T* denotes an outcome of "technology transfer" while *N* denotes "no technology transfer". The second subscript on the wage denotes the period in which it is paid.

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portion of the figures.

[4] I have asserted that the marginal cost is constant for each firm, but in fact this is only true up to the point that the supply of labor of the relevant skill level is exhausted. If the host firm's labor demand for the highest-trained workers exceeds the current supply, then to produce more output it will have to hire workers of a lower skill level. As noted in an earlier footnote, this issue will be discussed after the full model is presented; for the moment we (somewhat illegitimately) overlook it.

Table 1. Outcomes in period 1 in the one-period model.

	Wage		Output per worker		Unit Cost	
	w_S	w_H	q_S	q_H	c_S	c_H
N	w_{S1}	1	F[1, *l*]	1/Θ	w_{S1} / F[1, *l*]	*Q*
T	1	w_{H1}	F[1,1/*Q*]	1/*q*	1/F[1,1/*Q*]	$w_{H1}q$

As noted above, the issue is whether the host firm is willing to offer a high enough wage to persuade trained workers to defect from the source to the host firm; equivalently, the issue is whether there is some wage level which the host firm is willing to pay but the source firm is not willing to match, in which case defection and technology transfer occur. There are two advantages to the source firm in retaining its workers from one period to the next. One is that doing so denies these workers' services to the host firm, thereby keeping the host firm's marginal cost high, reducing its market share and profit, and raising the source firm's profit. The second advantage is that if the source firm retains its trained workers, its own next-period unit cost may be lower than if it does not retain these workers, and has to hire and train workers with a lower initial skill level – workers from the general labor pool, or from among former employees of the host firm.

If this were a multi-period model, we might have to take account of intertemporal considerations. But in the one-period model there are none, since neither firm can take any action in period 0 to affect the period-1 outcome, and period 1 is the last period. Thus the values of w_{S1} and w_{H1} are not hard to derive.

We find the highest wage the host firm is willing to pay by comparing the host firm's profit under *N* to its profit under *T* at a given wage. For each possible *w*, the host firm asks itself whether, if the source firm offered *w*, the host firm would be better off matching it or letting the source firm win the wage bidding. It does this by comparing its profit if it succeeds in hiring the most-trained workers at a given wage with its profit if it yields and lets its rival hire the same workers at that same wage.[5] The highest *w* which the host firm would match is the host firm's maximal wage offer. Thus the host firm looks at

$$p_H^N\left(c_S^N, c_H^N\right) - p_H^T\left(c_S^T, c_H^T\right) = p_H^N\left(\frac{w_{HH1}}{q_S^N}, \frac{1}{q_H^N}\right) - p_H^T\left(\frac{1}{q_S^T}, \frac{w_{HH1}}{q_H^T}\right) \qquad (1)$$

where each profit p is a function of the source (S) and host (H) firms' (constant) marginal costs (c_S, c_H) and the superscripts denote technology transfer (T) or no technology transfer (N), and where w_{HH1} denotes both w_S^N and w_H^T. Setting this expression equal to zero and solving for the unknown wage gives the host firm's maximal wage offer.

The reason is that expression (1) is negative for $w_{HH1} = 1$, since at this wage T implies lower host marginal cost and higher source marginal cost than N (the host acquires a more productive worker and lets a less productive worker move to the source firm). This means that when $w_{HH1} = 1$ the host firm prefers technology transfer if the source firm will allow it to occur. The expression in (1) is increasing in w_{HH1} (host profit under T falls with w and host profit under N rises with w), and for wage levels for which the expression is positive, the host firm will not contest a no-technology-transfer outcome. Thus setting expression (1) equal to zero and solving for w_{HH1} tells us the maximum wage level the host firm is willing to offer in order to secure technology transfer. We assume linear demand $p = a - b(Q_S + Q_H)$, where Q_j is firm j's total output.[6] Using a general result in Cournot competition when both firms have constant marginal cost and demand is linear, the profit for the host firm is given by $p_H(c_S, c_H) = (1/9b)(a - 2c_H + c_S)^2$. (This is derived in the usual way by writing profit as total revenue minus total cost, and finding both firms' reaction functions and their intersection, which gives output levels and profits.)

Substituting this into (1) and factoring, we see that the solution must satisfy $2c_H^N - c_S^N + 2c_H^T - c_S^T = 0$. We gain intuition by noting that in (c_S, c_H) space this says that the host firm isoprofit curves, for which it is easy to calculate an explicit equation, are straight lines with slope 1/2, as shown in Figure 2. So to find out whether any given cost combination (c'_S, c'_H) has equal host firm profit with another cost combination (c_S, c_H), we simply ask whether the slope of the line connecting them is equal to 1/2. In fact, the

[5] This wage determination procedure is different from that posed in Glass and Saggi (1999), because here I allow a wage counteroffer, in an attempt at greater realism. Thus one firm always pays a premium wage.
[6] While naturally it would be desirable to solve the game for more general demand curves, the complications in the linear case are sufficient that I have not yet attempted a more general solution.

sign of $\frac{(c_H^N - c_H^T)}{(c_S^N - c_S^T)} - \frac{1}{2}$ is the same as the sign of (1). In Figure 2 the host profit increases toward the lower right. This says that, using the point labels to represent the cost combinations pictured, $p_H(A) < p_H(B) = p_H(C) < p_H(D)$. By symmetry, the source firm isoprofit lines have slope 2, and p_S increases toward the upper left. Thus $p_S(B) > p_S A = p_S(C) > p_S(D)$. We want w_{HH1} which makes expression (1) equal to 0, and since $c_I = w_i / q_i$ with q the output per worker and $w_H^N = w_S^T = 1$, we make substitutions and solve for w_{HH1} to get:

$$w_{HH1} = \frac{\frac{2}{q_H^N} + \frac{1}{q_S^T}}{\frac{2}{q_H^T} + \frac{1}{q_S^N}} \qquad (2)$$

The derivation of the maximal wage offer the source firm will make in order to enforce N, denoted w_{SS1}, is exactly parallel. The source firm considers the expression

$$p_S^N\left(c_S^N, c_H^N\right) - p_S^T\left(c_S^T, c_H^T\right) = p_S^N\left(\frac{w_{SS1}}{q_S^N}, \frac{1}{q_H^N}\right) - p_S^T\left(\frac{1}{q_S^T}, \frac{w_{SS1}}{q_H^T}\right) \qquad (3)$$

where $w_{SS1} = w_S^N = w_H^T$. For $w_{SS1} = 1$, this expression is positive, because (as noted above) under N the source firm's marginal cost is lower and the host firm's marginal cost higher than under T, and hence source firm profit is higher under N than under T. So the source firm prefers that no technology transfer occur, and will match the host firm's wage offer. For wage levels that make the expression negative, there is no longer any advantage to the source firm in preventing technology transfer. Hence by setting equation (3) equal to zero and solving for w_{SS1}, we get the highest wage the source firm is willing to pay to prevent technology transfer. For linear demand this gives:

$$w_{SS1} = \frac{\frac{1}{q_H^N} + \frac{2}{q_S^T}}{\frac{1}{q_H^T} + \frac{2}{q_S^N}} \qquad (4)$$

We wish to compare w_{HH1} and w_{SS1} to see which firm will outbid the other for the services of the most-trained workers. The boundary between parameter values for which $w_{HH1} > w_{SS1}$ and those for which $w_{HH1} < w_{SS1}$ is of course given by $w_{HH1} = w_{SS1}$. So equating the right hand sides of (2) and (4) and simplifying, we find that $\frac{q_H^T}{q_H^N} - \frac{q_S^N}{q_S^T} = 0$.

Let us refer to the LHS of this equation as P (for pivotal value). In general, if $P = 0$ then it is readily shown that $w_{HH1} = \frac{q_H^T}{q_H^N} = \frac{q_S^N}{q_S^T} = w_{SS1}$. Since both firms stop bidding at the same wage level, either T or N could be said to occur.

For sets of parameter values which make $P < 0$, we have $\frac{q_H^T}{q_H^N} < w_{HH1} < w_{SS1} < \frac{q_S^N}{q_S^T}$ so that the source firm is willing to outbid any host firm wage offer to the most-trained workers. Hence the outcome is no technology transfer, and the wage that the source firm actually pays, denoted by w_{S1}, is w_{HH1} as given by equation (2), plus an arbitrarily small $\boldsymbol{e}$. For $P > 0$, we have $\frac{q_H^T}{q_H^N} > w_{HH1} > w_{SS1} > \frac{q_S^N}{q_S^T}$, so that technology transfer occurs, and the wage that the host firm actually pays, denoted by w_{H1}, is w_{SS1} given by equation (4). Notice that the sign of P is in general the same as the sign of $w_{HH1} - w_{SS1}$. Notice too that an alternative pivotal value, whose sign would also match that of $w_{HH1} - w_{SS1}$, is $q_H^T q_S^T - q_H^N q_S^N$; later we will often use this form for convenience.

We gain further intuition by returning to the (c_S, c_H) diagram. In Figure 3, define X – that is, (c_S^X, c_H^X) – as a point at which N occurs and at which $w = 1$. X lies on a host firm iso-profit line $\boldsymbol{p}_H = \boldsymbol{p}_H^X$ with slope 1/2, and on a source firm iso-profit line $\boldsymbol{p}_S = \boldsymbol{p}_S^X$ with slope 2. Source firm profit is higher than at X above and to the left of the iso-$\boldsymbol{p}_S$ line, and host firm profit is higher than at X below and to the right of the iso-$\boldsymbol{p}_H$ line. Hence in Figure 3, X is preferred by both firms to any point Y in region A. Likewise, any point in region C is preferred by both firms to X. If X is compared with any point Y in region B, the source firm prefers X but the host firm prefers Y. And symmetrically, if Y is in region D, the source firm prefers Y while the host firm prefers X.

Wage bidding can easily be shown in the diagram. In Figure 4, let X and Y represent two different scenarios such as N and T respectively, and let Y lie in X's region B so that the source firm prefers X while the host firm prefers Y. Define both X and Y as points at which $w = 1$ for both firms, so that X is $\left(\frac{1}{q_S^X}, \frac{1}{q_H^X}\right)$ and Y is $\left(\frac{1}{q_S^Y}, \frac{1}{q_H^Y}\right)$. Because

Y is in X's region B, the two firms have conflicting objectives, so both firms will bid up the wage. An increase in the source firm's wage offer is a move from X horizontally to the right, and we call this moving point X′; an increase in the host firm's wage offer is a move straight upward from Y, and we call this Y′. As long as these two wage bids are equal, the line segments are in the proportion OX′/OX = OY′/OY, or $c_S^{X'} / c_S^X = c_H^{Y'} / c_H^Y$.

The source firm stops bidding when the slope of X′Y′ is 1/2. Given the positions of X and Y shown in Figure 4, the line connecting X′ with Y′ rotates *clockwise* as X′ slides rightward and Y′ slides upward along their respective paths. Hence a slope of 2 is reached before a slope of 1/2; the source firm reaches its maximal wage offer w_{SS1} first; the host firm wins the wage bidding; Y is the outcome; and the host firm actually pays $w_{H1} = w_{SS1}$. If X and Y are drawn initially as in Figure 5, however, the line X′Y′ rotates *counterclockwise* as both firms make increasing matched wage bids, and X′Y′ reaches a slope of 1/2 before it reaches a slope of 2. In this case the host firm stops bidding first, the source firm's preference for X prevails, and the wage it pays is $w_{S1} = w_{HH1}$.

If X is the reference point, the boundary between these two different outcomes is the rectangular hyperbola passing through X, along which $c_S^X c_H^X = c_S^Y c_H^Y$ for any point Y on the hyperbola; and since $c = w/q$ and at X and Y only the reservation wage $w = 1$ is paid, this is equivalent to $q_S^X q_H^X - q_S^Y q_H^Y = 0$, the condition which was derived above. For this case, as shown in Figure 6, all the lines X′Y′ for equal wage bids are parallel, and both firms stop their wage bidding when the line degenerates to a single point, putting both firms on each others' "iso-profit lines". This point lies on a ray through (c_S^X, c_H^Y).

If at $w_S = w_H = 1$ we have given cost combinations X and Y, and without loss of generality we assume that at X, no-technology-transfer (*N*) occurs (no movement of workers among firms occurs), and at Y technology transfer (*T*) occurs (workers do move), then the following outcomes happen if Y is in the region shown in Figure 7, relative to X:

Table 2. Outcomes in (c_S, c_H) space.

Region	Outcome	Wage	Comment
B1	X	$w_{S1} = w_{HH1}$ $w_{H1} = 1$	Source firm wins wage bid; its preference for X prevails; workers do not move between firms.
B2	Y	$w_{H1} = w_{SS1}$ $w_{S1} = 1$	Host firm wins wage bid; its preference for Y prevails; workers move between firms.
C	Y	$w_{H1} = 1 + \varepsilon$ $w_{S1} = 1$	Both firms prefer movement of workers, so source firm does not bid above $w = 1$. Movement occurs.

Regions A, D1 and D2 are omitted from Table 2 because by reversing the roles of X and Y they can all be analyzed using B1, B2 and C in the table. For example, if Y is in X's D1 region, then X is in Y's B2 region.

So far this analysis has refrained from explicitly considering the part of the parameter space over which upgrading is not optimal for the source firm. We now do so. Suppose that in period j, parameter values may or may not cause the source firm to upgrade to the newest technology or (therefore) to train its workers. One situation in which a lack of upgrading can occur is in case no technology transfer occurs – that is, the source firm's wage bid is higher than the host firm's and it therefore retains its workers – and we denote this case by n (instead of N). The other case in which upgrading may fail to occur is when technology transfer does take place (the host firm bids higher and source firm workers do move to the host firm); we denote this case by t (instead of T). In the solution to the one-period game, the way this changes equations (2) and (4) is that q_S^T is replaced by Max[q_S^T, q_S^t], and all other source firm variables are replaced by a similar expression choosing which alternative (N or n), or (T or t) yields higher output per worker (q) for the period.

In Figure 8 we look at these decisions in (c_S,c_H) space for given q,Q, and g , allowing l to vary. (Figure 9 will show the same decision in (l,g) space, along a horizontal line representing the given g .)

First, suppose l = 0. The four points N_0, n_0, T_0, and t_0 represent each possible outcome when w = 1; their subscript is the value of l. In the (c_S, c_H) diagram the choice between N and n is a choice by the source firm between two points on a horizontal line; the same is true of its choice between T and t. Given the same c_H, the source firm of course chooses the point with lower c_S (higher q_S). In the case shown, it chooses n_0 over N_0, that is, for these parameter values, when $l = 0$ the source firm prefers not to upgrade if it wins the wage bidding because its profit is higher at n_0 than at N_0. But it also prefers T_0 over t_0 , so if it loses the wage bidding it does not upgrade. Once the source firm has made both these choices, then the wage bidding between the two firms proceeds based on n vs. T, and the final outcome is given by Table 2[7], based on the initial relative positions of the two points at $w = 1$. In this case T_0 is in n_0's B2 region, so the bidding between outcome n_0 and outcome T_0 is won by the host firm, and T_0 prevails. The point $(q, Q, l, g) = (1.5, 1.6, 0, 1.9)$ therefore lies in a region of (l,g) space in which T is the outcome, as Figure 9 shows.

What happens as l increases, that is, as we move to the right along a horizontal line in Figure 9? Both N_l and T_l move to the left in Figure 8, because upgrading and training are less costly to the source firm at higher l, while n_l and t_l stay put at n_0 and t_0, since their coordinates do not involve l. In this case, at some l, N_l passes through n_0 and so becomes preferred to n_l, while T_l remains preferred to t_l, so that the wage bidding then proceeds based on N vs. T. (However, since T was winning the wage bidding already, this does not immediately affect the final outcome.) In this case, this happens at $g = 2/(1 + l)$, or $l = (2.0/1.9) - 1 = 0.05$. If N_l moves to the left much faster than T_l (or if the c_H's are very close as shown in Figure 8), then at some l the two points N_l and T_l will lie on a rectangular hyperbola, and once this is crossed, the source firm will win the wage bidding and N will be the outcome. Thus as we move to the right on a horizontal line in Figure 9, the source firm eventually begins to win the wage bidding, and technology transfer ceases to occur. In the case shown, this boundary occurs at $l = (Q - q)/q - 1) = 0.1/0.5 = 0.2$, corresponding to the pivotal value for N vs. T, and this boundary is shown in (l,g) space in Figure 9. Table 2 shows the cost structure at $l = 0$ and $l = 1$.

We now allow all parameters to vary and derive all such boundaries, in each case using the pivotal values. In Table 3, all possible comparisons between pairs of outcomes

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[7] Note that the source firm's choice, e.g. between N and n, by which has the higher output per worker, is equivalent to using the pivotal value $q_H^N q_S^N - q_H^n q_S^n$ where $q_H^N = q_H^n$ since the host firm's output in the

are shown. A pivotal value for each comparison of outcome *j* with outcome *k* is given by P = $q_{H1}^{j}q_{S1}^{j} - q_{H1}^{k}q_{S1}^{k}$. When P > 0, outcome *j* trumps outcome *k* and we write *j* > *k*. When P < 0, this "inequality" is reversed and *j* > *k*. The pivotal values are shown in Table 4. For P_A, P_B, P_D and P_E, *g* appears in the expression, so when each of these is equated to 0 we have *g* explicitly as a function of l and the other parameters and this gives us a curve in (l,*g*) space which is the boundary between two outcomes.

Table 3. For the one-period game, output per worker for both firms under all outcomes, and resulting pivotal values comparing each pair of outcomes.

j	q_H	q_S	***k***	q_H	q_S	$q_H^j q_S^j - q_H^k q_S^k$
N	1/*Q*	F[1, l]	***n***	1/*Q*	F[0,1]	(1/*Q*)F[1, l] – (1/*Q*)F[0,1]
T	1/*q*	F[1, l/*Q*]	***t***	1/*q*	F[0,1/*Q*]	(1/*q*)[1, l/*Q*] – (1/*q*)F[0,1/*Q*]
N	1/*Q*	F[1, l]	***T***	1/*q*	F[1, l/*Q*]	(1/*Q*)F[1, l] – (1/*q*)F[1, l/*Q*]
N	1/*Q*	F[1, l]	***t***	1/*q*	F[0,1/*Q*]	(1/*Q*)F[1, l] – (1/*q*)F[0,1/*Q*]
T	1/*q*	F[1, l/*Q*]	***n***	1/*Q*	F[0,1]	(1/*q*)F[1, l/*Q*] – (1/*Q*)F[0,1]
n	1/*Q*	F[0,1]	***t***	1/*q*	F[0,1/*Q*]	(1/*Q*)F[0,1] – (1/*q*)F[0,1/*Q*]

For P_C and P_F, however, *g* does not appear in the equations. P_C = 0 is a vertical line in (l,*g*) space; P_F involves only *q* and *Q*, so it is not a curve on the graph in Figure 10a at all. Instead, P_F = 0 defines two cases, one shown in Figure 10a and one in Figure 10b, depending on whether P_F = 2*q* – (1+ *Q*) is positive or negative. Notice that P_F can be written as (*q* – 1) – (*Q* – *q*) so that P_F 0 implies that P_C = 0 is a vertical line at some l 1; but if P_F 0 we must have P_C 0 since we require 0 l 1, and this means the vertical line is no longer present on the graph.

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current period is unaffected by whether the source firm upgrades and trains in the current period.

Table 4. For the one-period game, use of pivotal values marking boundaries of regions of the parameter space in which different outcomes occur.

i	P_i, general form	P_i (simplified) for $C(s) = (1/2)(1-s)$	Outcome if $P_i > 0$
A	$F[1,l] - F[0,1]$	$g - 2/(1 + l)$	$N > n$
B	$F[1,l/Q] - F[0,1/Q]$	$g - (1 + Q)/(l + Q)$	$T > t$
C	$(1/Q)F[1,l] - (1/q)F[1,l/Q]$	$l - (Q - q)/(q - 1)$	$N > T$
D	$(1/Q)F[1,l] - (1/q)F[0,1/Q]$	$g - (1 + Q/(q(1 + l))$	$N > t$
E	$(1/q)F[1,l/Q] - (1/Q)F[0,1]$	$g - 2q/(l + Q)$	$T > n$
F	$(1/Q)F[0,1] - (1/q)F[0,1/Q]$	$2q - (1 + Q)$	$n > t$

Figure 10 shows all the relevant curves and the cases they distinguish, illustrated for the case $q = 1.5$, $Q = 1.6$. However, logical relationships among the possible outcomes reduce the final outcome to the simpler diagrams in Figure 11. An example shows how this works. The region of Figure 10a denoted **n*** lies below curves A and E, to the right of curve C, and above curves B and D. Hence in this region $n > N$, $n > T$, $N > T$, and $T > t$. These tell us that $n > N > T > t$, so n is the outcome in this region. The complete set of outcomes cannot be shown in one diagram, but it can be shown in two. The case $P_F > 0$ is shown in Figure 11a (for $q = 1.5$, $Q = 1.6$); in this case, boundaries A, C, and E and F completely determine the outcomes. The case $P_F < 0$ is shown in Figure 11b (for $q = 1.5$, $Q = 2.1$); in this case boundaries B and F alone completely determine the outcome.

In the one-period game, what can we conclude about the circumstances under which technology transfer occurs? The analysis summarized in Figure 11 shows that there are two main ways that technology transfer with upgrading and training (T) will take place. One is if in Figure 11a we are in the upper left corner where $P_C > 0$ (to the left of line C) and $P_E > 0$ (above curve E). This means that both of the following are true:

(a) upgrading and training are optimal for the source firm, even if the trainees are from the general labor pool, because the productivity gain from upgrading to a new vintage (g) is large enough to more than offset the cost of training due to imperfect transferability of skills to the new vintage (l) and the low baseline skill level of untrained workers (Q); that is, $P_E > 0$);

(b) $l < (Q - q)/(q - 1)$, that is, roughly speaking, the host firm's labor saving from hiring a trained instead of an untrained worker $(Q - q)$, relative to the labor saved when a trained worker works in the source firm instead of the host firm $(q - 1)$, is greater than the degree of transferability of skill from one vintage to the next (l). The logic here, loosely speaking, seems to be that if the cost to the source firm of letting a trained worker go is less than the gain to the host firm of getting that worker, then the host firm will win the wage bidding and technology transfer will occur.

Another main way in which technology transfer with upgrading and training (*T*) can occur is if we are in Figure 11b and above curve B, where $P_B > 0$, that is, if both of the following are true:

(c) the productivity gain to the host firm from employing a trained worker relative to an untrained worker is small, that is, $q - 1 < Q - q$, or in other words $2q < 1 + Q$; and

(d) the productivity gain to the source firm upon upgrading (g) is sufficiently large, or the transferability of skills from one vintage to the next (l) is sufficiently large, and/or untrained workers are sufficiently unproductive, that is, $g > (Q + 1)/(Q + l)$, which is more likely with high Q, l and g .

If (c) is satisfied, but not (d), then we are in the lower left corner of Figure 11b and technology transfer will still occur, but the source firm will neither upgrade nor train. We now examine the two-period model to see how it changes the region of parameter values over which technology transfer occurs.

B. The two-period model

In the "two-period" model (initial period 0, followed by periods 1 and 2), intertemporal considerations come into play. Two things are new in the two-period game. First, with each additional period that passes in which *N* occurs (the source firm retains the same workers, upgrades to a newer vintage of technology, and trains these workers to operate it), the source firm's productivity advantage over the host firm grows. Hence with each period in which *N* occurs, the greater in the next period is the gain to the host firm by recruiting recently trained source firm workers, and the higher the host firm's wage bid will be to try to recruit these workers. Our analysis of the one-period game has shown that the larger the gap between the current productivity level of host firm workers and the level that could be attained by recruiting trained source firm workers (that is, the larger is Q relative to q), the more likely are conditions (c) and (d) above to be satisfied. Hence, the more likely is the host firm to win the wage bidding and the more likely, therefore, is technology transfer to occur.

Second, period-1 wage decisions may now be affected by the prospect of the next period. Let us denote the outcomes by two letters, the first giving the period-1 outcome (N, n, T or t) and the second similarly giving the period-2 outcome. For example, the outcome nT means the source firm retained its workers in period 1 but did not upgrade or train them, and then in period 2 they moved to the host firm while the source firm hired workers from the general labor pool, upgraded to vintage 2 and trained these workers in it. It turns out that technology transfer in period 1 can present the host firm with a more favorable game to play in period 2, and so in order to get it the host firm may pay a higher period-1 wage than in the one-period model. For instance, if N will be the outcome in period 2, then the host firm prefers that T occurred in period 1. The reason is that technology transfer in period 1 guarantees the host firm a workforce trained in vintage 0, and this improves the host firm's period-2 fallback position if no technology transfer occurs. This host firm fallback position is to retain the same vintage-0-trained workforce and continue operating vintage 0 using these fairly productive workers, at lower marginal cost than if it had to produce using untrained workers. To bolster its period-2 fallback position, then, the host firm might be willing to offer a higher period-1 wage than in the one-period game in order to get technology transfer in period 1 and reap period-2 gains.

We have 16 possible two-period outcomes: $\{N, n, T, t\} \times \{N, n, T, t\}$, which we write in abbreviated form, grouped in anticipation of our next step, as $\{\{\{NN, Nn\}, \{NT, Nt\}\}, \{\{nN, nn\}, \{nT, nt\}\}, \{\{TN, Tn\}, \{TT, Tt\}\}, \{\{tN, tn\}, \{tT, tt\}\}\}$. Though the problem could now multiply in complexity, it turns out that by using the pivotal values we can greatly simplify the solution procedure.[8]

[8] The observant reader may notice that in the two-period game, it is possible that three skill levels may eventually exist among the labor force: those with only the baseline level of skill, those trained only in vintage 0, and those trained in vintage 1. In principle we might therefore have to calculate several wage levels. However, because this is a duopoly game, and workers with less than the highest level of training

First we derive the period-2 outcome that follows each possible period-1 outcome. We do this in two stages, as before. In stage one the source firm decides whether to upgrade in period 2, given a particular period-1 outcome. In other words, from each pair the source firm chooses one: either *NN* or *Nn*, either *NT* or *Nt*, and so on, eight decisions in all, reducing the size of the list to 8 possible outcomes, in four groups of two each.

In stage 2, both the source and host firm make wage bids for period 2 and one firm wins, determining that period's outcome for each given period-1 outcome. This reduces the list to four outcomes, one each for an outcome of *N*, *n*, *T*, or *t* in period 1. Thus for each point in the 4-dimensional (q, Q, g, l) parameter space we now have a list of four possible outcomes. A similar decision-making process follows for period 1 (with some wrinkles to be explained later), determining the single two-period outcome that occurs for each point in the parameter space. An example will make matters clearer.

Suppose for the moment that *N* occurred in period 1. The source firm decides whether to base its stage 2 wage bid on *NN* or *Nn*, that is, on upgrading or not in period 2 in case it succeeds in retaining its workers. To make this decision, the source firm compares p_{S2}^{NN} with p_{S2}^{Nn}, its profits associated with each outcome. This is easy to do, since $c_{H2}^{NN} = c_{H2}^{Nn}$, that is, the host firm's period-2 marginal cost is unaffected by whether or not the source firm upgrades in period 2. Hence the boundary in the parameter space between its choice of *NN* and its choice of *Nn* occurs when $c_{S2}^{NN} = c_{S2}^{Nn}$. At a given wage this occurs when $q_{S2}^{NN} = q_{S2}^{Nn}$, or from Table A1 in the Appendix showing q for each outcome and each period, when F[2,l] = F[1,1]. We therefore define P_1 = F[2,l] – F[1,1], and refer to P_1 as a pivotal value analogous to our earlier use of that term. For $P_1 > 0$, the source firm prefers *NN*. For $P_1 < 0$, it prefers *Nn*.

This decision between *NN* and *Nn* is one of the eight decisions that need to be made in stage 1. In all these eight comparisons between upgrading and not upgrading, the q_H terms drop out in the same way, since the source firm's decision to upgrade or not in the current period never affects the host firm's current-period marginal cost. Thus in

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have as alternative employment income only the reservation wage, the firm that loses the wage bidding for the most-trained workers can get away with paying any less-trained worker the reservation wage plus an arbitrarily small premium, which we can safely ignore. It is worth mentioning here that in the interest of simplicity, much of the rich literature on wage determination is being ignored. A brief discussion toward the end of this paper will try to repair some of the damage.

each case we make the choice simply comparing source firm outputs per worker under the two alternatives. Further, some expressions recur, and it turns out that all eight decisions can be reached by the use of just three conditions: P_1 , P_2 and P_3. If $P_1 > 0$, then as before we will write *NN* > *Nn*, meaning that the source firm chooses *NN* over *Nn* (an abuse of notation since neither *NN* nor *Nn* is a number). Then, for example, if $P_1 > 0$ we have both *NN* > *Nn* and *TN* > *Tn*. The three conditions are:

(1) $P_1 = F[2, l] - F[1,1]$ (if positive, *NN* > *Nn*} and *TN* > *Tn*)

(2) $P_2 = F[2, l^2] - F[0,1]$ (if positive, *nN* > *nn*, *TT* > *Tt*, and *tT* > *tt*); and

(3) $P_3 = F[2, l^2/Q] - F[0,1/Q]$ (if positive, *NT* > *Nt*, *nT* > *nt*, and *tN* > *tn*).

If the cost function is defined as $C(s) = (1/2)(1 - s)$, then it is always true that P_1 P_2 P_3; the proof is given in the Appendix. This is illustrated in Figure 12, where $P_1 = 0$ lies above $P_2 = 0$, which in turn lies above $P_3 = 0$, except at (1,1), where they all coincide. For this cost function the three curves are respectively given by:

(1a) $P_1 = g - 2/(1 + l) = 0$;

(2a) $P_2 = g - [2/(1 + l^2)]^{1/2} = 0$;

(3a) $P_3 = g - [(1 + Q)/(l^2 + Q)]^{1/2} = 0$.

Thus the plausible region of the (l, g) plane shown, namely $l \in [0,1]$ and $g \in [1,2]$, is divided into four regions, for each of which Table 5 below shows the eight outcomes of the stage 1 decisions, also shown in Figure 12.

Table 5. Possible outcomes remaining after source firm decides whether to upgrade in period 2, for four regions of the parameter space.

P_1	P_2	P_3	Possible outcomes after source firm's stage 1 decision
+	+	+	{*NN*, *NT*, *nN*, *nT*, *TN*, *TT*, *tN*, *tT*}
–	+	+	{*Nn*, *NT*, *nN*, *nT*, *Tn*, *TT*, *tN*, *tT*}
–	–	+	{*Nn*, *NT*, *nn*, *nT*, *Tn*, *Tt*, *tN*, *tt*}
–	–	–	{*Nn*, *Nt*, *nn*, *nt*, *Tn*, *Tt*, *tn*, *tt*}

Thus, for example, in Figure 12 in the region above the curve $P_1 = 0$, *NN* > *Nn* and *TN* > *Tn*, while below the same curve, *Nn* > *NN* and *Tn* > *TN*. Likewise, above $P_2 = 0$ we have *nN* > *nn*, as well as *TT* > *Tt* and *tT* > *tt*; below $P_2 = 0$ the reverse of each is true.

Notice that above $P_1 = 0$ the source firm always upgrades, and below $P_3 = 0$ it never does. This completes stage 1.

In stage 1, eight comparisons were made. In stage 2, 16 other comparisons potentially could be made, those shown in Table A2, lines 9-24, in the Appendix. Each is a comparison between either *N* or *n* on one side (in period 2) and either *T* or *t* on the other, following the same hypothetical period-1 outcome. So, for example, the four pairs we compare assuming *N* in period 1 are {{*NN*, *NT*}, {*NN*, *Nt*}, {*Nn*, *NT*}, {*Nn*, *Nt*}}. It turns out that a few of these comparisons are unnecessary, however, because stage 1 always eliminates them. For example, *NN* never faces off against *Nt* in the stage 2 wage bidding, because, as Table 5 shows, it does not occur in any of the four regions (this is because, moving down the chart, *NN* changes to *Nn* before *NT* changes to *Nt*). Likewise, the comparisons {*nN*, *nt*}, {*TN*, *Tt*} and {*tn*, *tT*} do not occur.

The outcomes of the remaining 12 comparisons are determined by the use of just the following six additional conditions P_4 – P_9, plus condition P_2 which is repeated here to list the additional outcome it determines:

Table 6. Pivotal values for period 2 outcomes of wage bidding.

	P_i , general expression	***P_i if $C(s) = (1/2)(1 – s)$**	**Outcome if $P_i > 0$**
P_2	$F[2, l^2] – F[0,1]$	$g – [2/(1 + l^2)]^{1/2}$	*TT* > *Tn*
P_4	$(g/q)F[2, l^2/Q] – (1/Q)(F[2, l])$	$g – q(1 + l)/(Q + l^2)$	*NT* > *NN*
P_5	$(g/q)F[2, l^2/Q] – (1/Q)(F[1,1])$	$g – [2q/(Q + l^2)]^{1/2}$	*NT* > *Nn*, *nT* > *nn*, *tN* > *tt*
P_6	$(g/q)F[0,1/Q] – (1/Q)(F[1,1])$	$2q – (1 + Q)$	*Nn* > *Nt*, *nn* > *nt*, *tt* > *tn*
P_7	$(1/Q)(F[2, l^2] – (1/q)F[2, l^2/Q]$	$q + (q – 1) l^2 – Q$	*nN* > *nT*, *tT* > *tN*
P_8	$(1/q)F[2, l] – (g/q)F[2, l^2]$	$g – (1 + l)/(1 + l^2)$	*TT* > *TN*
P_9	$(1/q)(F[1,1] – (g/q)F[0,1]$	$(1/q)g – (g/q)(1)$ (always = 0)	*Tn*~*Tt* (firms are indifferent between *Tn* and *Tt*)

*The expression is simplified by factoring out terms which are always positive; in the second line, for instance, $g^2(1 + l^2/Q)/q$ has been factored out.

In each case, if $P_i < 0$ the “inequalities” in the last column are reversed.

Perhaps here is the place to point out that the occurrence of *t* in period 1 introduces an anomaly into the two-period game which is not present in the one-period game. When *t* occurs in period 1, then in period 2 the general principle – that the source firm prefers *N* or *n* and the host prefers *T* or *t* – does not hold true. If *t* happens in period 1, the workers trained in vintage 0 move from the source to the host firm, and the source firm employs workers with no training, and moreover refrains from training them. Thus in period 2, following *t* in 1, at $w = 1$ the source firm prefers that *t* occur rather than *n*, and so is willing to offer a wage premium in order to prevent *n* from occurring; this is because *n* would leave the source firm with the same untrained, low-productivity workers it acquired in period 1.

Likewise, in the contest between *tT* and *tN*, the source firm will always prefer *tT* at $w = 1$, and so will offer a wage premium in order to get it. And in the region of the parameter space in which the period-2 contest is between *tN* and *tt*, the source firm will always prefer *tt* and the host firm will always prefer *tN*.[9] For these three cases, then, we can use essentially the same method of analysis, writing expressions for w_{HH2} and w_{SS2} and equating them to find the boundary between two outcomes; or equivalently, simply using the pivotal value as before (being careful to notice which outcome prevails on which side of the boundary). As for the case *tn* vs. *tT*, we have already observed that this case does not occur, since stage 1 eliminates it.

This completes the analysis of stage 2, and its results are summarized in Table 7. For each region of the parameter space – with each region now defined by the signs of the 7 P_i expressions – we have reduced the list of possible two-period outcomes to four: each possible period-1 outcome implies a single period-2 outcome, based on the signs of the 7 P_i. The notation *Tn~Tt* means that the firms are indifferent to which of these two period-2 outcome occurs, since the profit from *n* or *t* in period 2, given *T* in period 1, is identical for all sets of parameter values in the region.

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[9] This is proved in the Appendix.

Table 7. Period-2 outcomes that follow from period-1 outcomes, determined by pivotal values.

P_1	P_2	P_3	P_4	P_5	P_6	P_7	Outcomes
±	+	+	+	+	+	+	*NT, nN, TT, tT*
±	+	+	+	+	+	–	*NT, nT, TT, tN*
+	+	+	–	±	+	+	*NN, nN, TT, tT*
–	+	+	±	–	+	+	*Nn, nN, TT, tT*
–	–	+	+	+	±	–	*NT, nT, Tn~Tt, tN*
–	–	±	±	–	+	±	*Nn, nn, Tn~Tt, tt*
–	–	–	+	±	–	–	*Nt, nt, Tn~Tt, tn*

Because of the logical relationships among the signs of the P_i, some combinations do not appear in the table, since they cannot occur in practice. For example, algebraically, if P_7 is +, then P_6 must be + also. Likewise, if P_3 is –, then neither P_1 nor P_2 can be +. Further details are given in the Appendix.

Figure 13 shows these regions of period-2 outcomes for q = 1.5. The left column is for the case in which $P_6 > 0$ and so the vertical line $P_7 = 0$ is part of the diagram; the diagram is based on Q = 1.65. The right column is for the case in which $P_6 < 0$ and so P_7 must be < 0 for l between 0 and 1; thus the vertical line $P_7 = 0$ is outside the diagram; for the case drawn, Q = 2.3. These diagrams differ somewhat from the one-period diagrams because in period 2 the cost structure is a little different. This completes the analysis of period 2, and we now turn to the analysis of period 1.

The next step is for the source firm to figure out what its maximal wage offer would be for each pair of opposing period-1 outcomes: for *N* vs. *T*, for *N* vs. *t*, for *n* vs. *T*, and for *n* vs. *t*. In each case it knows (from Table 7 or Figure 13) which period-2 outcome would follow from each period-1 outcome, so in deciding its wage offer it takes account of the intertemporal effects. It does so in the following way.

We define a function *R* for each firm which is its total profit for both periods 1 and 2, when the period-1 outcome is *i* and the period-2 outcome is *j*:

$$R_H^{ij} = p_{H1}^{ij}(c_{S1}^{ij}, c_{H1}^{ij}) + p_{H2}^{ij}(c_{S2}^{ij}, c_{H2}^{ij})$$

$$R_S^{ij} = p_{S1}^{ij}(c_{S1}^{ij}, c_{H1}^{ij}) + p_{S2}^{ij}(c_{S2}^{ij}, c_{H2}^{ij})$$

Suppose, for example, that both the source and the host firm are comparing option *Nx* with option *Ty*, where *x* represents whatever outcome follows *N*, based on the result of the stage-2 decision for the given set of parameter values, and *y* represents whatever outcome follows *T*. The source firm's maximal wage offer to its workers in period 1 is the wage which satisfies:

$$R_S^{Nx} - R_S^{Ty} = 0 \tag{11}$$

Writing out the profits as functions of marginal costs, and making substitutions where the wage or the output per worker is equal to unity, this condition becomes:

$$p_{S1}^{Nx}\left(\frac{w_{SS1}}{q_{S1}^{Nx}}, \frac{1}{q_{H1}^{Nx}}\right) + p_{S2}^{Nx}\left(c_{S2}^{Nx}, c_{H2}^{Nx}\right) - p_{S1}^{Ty}\left(\frac{1}{q_{S1}^{Ty}}, \frac{w_{SS1}}{1}\right) - p_{S2}^{Ty}\left(c_{S2}^{Ty}, c_{H2}^{Ty}\right) = 0 \tag{11a}$$

Notice that the unknown wage appears only in the first and third terms, and the remaining values of *c* and *q* either are given or have already been calculated in stages 1 and 2. When demand is linear, this is a quadratic equation which we solve for the unknown wage, giving the source firm's maximal wage offer to get *Nx* instead of *Ty*. The parallel equation to get the host firm's maximal wage offer to get *Ty* instead of *Nx* is of course:

$$p_{H1}^{Nx}\left(\frac{w_{HH1}}{q_{S1}^{Nx}}, \frac{1}{q_{H1}^{Nx}}\right) + p_{H2}^{Nx}\left(c_{S2}^{Nx}, c_{H2}^{Nx}\right) - p_{H1}^{Ty}\left(\frac{1}{q_{S1}^{Ty}}, \frac{w_{HH1}}{1}\right) - p_{H2}^{Ty}\left(c_{S2}^{Ty}, c_{H2}^{Ty}\right) = 0 \tag{12}$$

The source firm calculates both firms' maximal wage offers and hence the outcome, for each possible period-1 contest: *N* vs. *T*, *N* vs. *t*, *n* vs. *T*, and *n* vs. *t*. From the outcome and the actual wage paid (namely, the losing bidder's maximal wage offer), the source firm calculates the profit it would earn from each contest, and chooses the one with the highest profit. In other words, it chooses whether to upgrade in case it wins the wage bidding (chooses *N* or *n*), and whether to upgrade in case it loses the bidding (chooses *T* or *t*). This defines the period-1 contest, and once the source firm has made these calculations, it also knows the outcome of that contest and the wages that will be paid.

As before, we may also approach the problem by finding the boundary between two different outcomes, that is, the locus of parameter values for which both firms' maximal wage offers are equal. By solving (11a) and (12) simultaneously for the unknown wage, we get a relationship among the model's four main parameters q, Q, g and l, defining the multi-dimensional boundary between the occurrence of *Nx* and of *Ty*.

Rather than explicitly calculate these boundaries, I have used *Mathematica* (*2.2*) to plot outcomes at intervals over the whole relevant region of the parameter space, namely, the hyper-rectangle $l \in [0,1]$, $g \in [1,2]$, $q \in [1,2]$, $Q \in [q,3]$. (I have also plotted results for other combinations of q and Q; for fixed q and for Q beginning at $q + 0.1$ and rising, the results look quite similar.) In Figure 14 the results are plotted in (l,g) space for $q = 1.5$ and various values of Q. The results have also been plotted for $q =$ 1.5, and $Q = 1.6$, 1.7, 1.8, 1.9 and 2.0, and the plots look very similar to those shown. (For all these plots, the constants a and b in the price function were taken as $a = 10$ and $b = 1/9$; the value of a was chosen to ensure that the plots did not include a region in which the host firm's profit dropped to zero, and the value of b is of no consequence since it drops out of the calculations.) We can draw the following conclusions – a few of which have already been mentioned – again for the case in which $C(s) = (1/2)(1 - s)$:

(1) Upgrade and training always occur in the source firm if the gain in best-practice productivity is large enough from one vintage to the next, and if skill carries over sufficiently from one vintage to the next. That is, upgrade and training occur if g is large enough, or l is large enough, or both, i.e., whenever $P_1 > 0$ (above curve 1 in Figure 12, that is, whenever $g > 2/(1 + l)$).

(2) Upgrade and training never occur if the productivity gain from upgrading and training is too small to offset the cost of training. That is, upgrade and training fail to occur whenever g is small and/or l is small, i.e., when $P_3 < 0$ (below curve 3 in Figure 12) that is, whenever $g < [(1 + Q)/(l^2 + Q)]^{1/2}$.

(3) The larger is $(Q - q)/(q - 1)$, the wider is the range of parameter values over which technology transfer in period 2 occurs; large Q and small q, for example, can bring this about. Again, this result is similar, but not identical, to the result obtained by Glass and Saggi (1999) in a related model. In other words, when a trained worker has significantly greater productivity in the host firm than an untrained worker, then in both periods the host firm wins the wage bidding over a wide range of (l,g). In particular, $P_6 < 0$ guarantees that if upgrade and training occur, technology transfer will occur in both periods for almost all plausible parameter sets.

(4) Technology transfer is more likely in period 2 than in period 1 (where "likelihood" is a loose way of referring to the size of region of the parameter space over which the result occurs). This appears to be because the host firm is willing to make a

higher wage bid in period 2 than in period 1 to recruit skilled workers. Probably this is because the host firm's productivity gap widens further with each successive period, and the advantage to the host firm of recruiting a recently trained worker (or the disadvantage of not doing so) correspondingly increases.

(5) Virtually every possible two-period outcome occurs for some set of parameter values, even if the set is quite small. And what matters is not the size of the region over which the outcome occurs, but how likely that combination of parameter values is to occur in practice. For example, *NN* occurs only where l is large, g is around 1.1-1.2, and q is close to Q, but these may well be very plausible values of the parameters.

III. Labor markets

The model presented here has been based on implicit and explicit assumptions about the functioning of labor markets, which now deserve some discussion. We will consider four issues. The first is the one noted in a previous footnote: that marginal cost cannot actually be constant for all levels of output, since the supply of workers of a given skill level is finite at any given time. The second and third issues have to do with the role of workers as possible players in the game: the second is whether Becker-type effects occur, with workers from the general labor pool "paying" the cost of training by accepting lower wages; the third is whether workers simply accept the highest current wage offer (as assumed here), or whether they consider the present value of present and expected future wages. If workers consider the present value of wages, then in a given period the host firm might have to offer more than e above the source firm's wage offer to persuade workers to leave the source firm; it might have to offer a premium which fully compensates them for lost access to future training and associated wages in the source firm. The fourth issue is whether the host firm might hire source firm workers not just as employees, but as trainers of other employees.

The first issue is what happens when we recognize that marginal cost curves are not always flat. We assumed in presenting the model that in a given period marginal cost c was constant for a given firm, in the sense of being independent of the level of total output the firm chose to produce during the period. Since the supply of labor of a given skill level is fixed and finite at any moment, however, this assumption is not valid. The marginal cost curve is actually a step function with one or more jump discontinuities. If demand for labor of the highest current skill level exceeds the supply, this discontinuity will affect the outcome. We therefore ask how taking account of this fact would change the results. We will make a heuristic argument that doing so would not change the qualitative features of the results in any major way. Most likely the source firm would win the wage bidding over a wider range of parameter values, so n or N would occur over a wider range, but the general shape of the results should be similar.

In a Cournot duopoly model with constant marginal cost, each firm's labor force depends on both firms' marginal costs and on wage or (equivalently) on output per worker. The host firm's demand for labor is $L_H = Q_H/q_H$, where Q_H is the total host firm output, and using the standard Cournot result for Q_H, we have $L_H = (1/3b)(a - 2c_H + c_S)/q_H$. Similarly, $L_S = (1/3b)(a - 2c_H + c_S)/q_S$. We gain some intuition by noting that when $c_S = c_H$, we have $w_H/w_S = q_H/q_S$, and both firms have the same total output as well as the same wage bill ($w_H L_H = w_S L_S$), and the ratio of the labor forces is the ratio of outputs per worker: $L_H/L_S = q_H/q_S$. However, deriving precise results where the marginal cost curves of one or both firms are not flat, and where there are intertemporal effects to take account of, is a bit complex. Instead, we make the following argument.

First, due to the partial transferability of skill to the host firm (described by q), the host firm's demand for labor of the highest skill level is more likely to exceed the current supply than is the source firm's demand for labor. When this occurs, the host firm's marginal cost curve has a step upward when, to meet its demand for labor, it must dip into labor of the next-lower skill level. However, it will also pay this labor a lower wage, namely $(1 + e)$, even when it pays a premium wage for the highest skill, so the step need not be large. This will evidently cause the host firm to make a somewhat lower maximal wage offer than equation (2), since as its wage offer to the highest-skilled workers rises, its profit will fall to equality with its profit from the alternative outcome at a somewhat lower wage than (2).

It should be noted that it is possible that the source firm not only wins the wage bid and upgrades but that it also downsizes; if this happens it allows the host firm to hire these downsized workers at $w = (1 + e)$, and this, by raising the profitability to the host firm of a source firm win, will also reduce the host firm's maximal wage offer. Notice that if this happens, a little technology transfer actually does occur through these laid-off workers, even though the outcome is *N*, which we have called “no technology transfer”.

In sum, *N* may happen over a wider range of parameter values than in Figure 14 if we take account of the true marginal cost curves, but in some instances *N* will allow for some technology transfer in fact to occur. The general conclusions arrived at assuming constant marginal cost should hold, and the qualitative features in Figure 14 should remain valid. It remains for future research, probably through simulation, to derive the exact outcomes.

The second issue is that we have assumed that workers simply passively accept whatever is the highest wage offer in the current period, without giving any thought to the implications for their possibilities for future wage earnings. We have assumed that no worker makes a lower wage offer to the source firm in order to receive preferential hiring and get access to training opportunities. How does this analysis mesh with Becker’s theory of general and specific training? In Becker (1993), if the labor market is competitive, training which is usable equally in any firm is referred to as “general” training. In contrast, training which is useful only to one firm is referred to as “completely specific”. Becker asserted that in a competitive labor market general training would tend to be paid for by workers themselves, because a firm had no way to ensure that if it invested in training its employees it would reap the return from that training. On the other hand, Becker argued, the cost of specific training would be shared between the firm and the worker, in unspecified proportions, in order for each to ensure that the other would not initiate separation of the employment relationship before the full anticipated return was earned by both parties.

Stevens (1994a,b) observes that the vast majority of training is neither perfectly general nor perfectly specific, but is usable in some firms and not others, and is not productive to the same degree even in all the firms where it is usable. She calls this type of training “transferable”, and argues that it is inappropriate to assume that it can be treated as a composite of general and specific components. She offers an analysis of a particular model in which training is transferable only, and in which there is imperfect competition in the labor market.

The model presented here has the interesting feature that training may be viewed as transferable but not as completely general or completely specific, for a reason partly different from that cited in other literature. Here training is transferable because of the repeated upgrading to a new vintage of technology and the lag before the host firm can acquire technology from the source firm. In period j in which a worker becomes trained by the source firm, the host firm cannot hire her and is operating an earlier vintage of technology. But by the time the host firm can hire her and exploit her vintage j expertise, the source firm may be operating vintage $j + 1$, and her skills are therefore relatively less valuable to the host firm in the context of duopoly competition in which the rival source firm has become still more productive. Further, the worker's skills are only partly transferable from the source to the host firm, due to the factor q. Hence in this sense, too, training is only transferable, not general and not completely specific.

Given that the training which the source firm provides does lead to higher wages, either in the source or the host firm depending on whether N or T occurs, why wouldn't workers from the general labor force offer, in effect, to pay for their training themselves, driving average multi-period wage earnings down to the reservation wage? Glass and Saggi, in their simpler model, exclude this possibility by assuming that workers have no access to credit, and so cannot make an up-front payment in order get preferential hiring in the source firm. However, all that is needed in the present model is for workers to sign an enforceable contract agreeing to turn over any wage earnings above the reservation wage to the source firm, even if the premium wages are actually earned in the source firm. The source firm itself would extend credit to the workers. Thus in principle Becker effects could be incorporated into this model.

However, some substantial recent theoretical and empirical research argues that employers at least sometimes pay for training which is general, and that there are sound theoretical reasons why they might do so, focused mainly on labor market imperfections. Acemoglu and Pischke (1999) make this argument and cite a number of relevant studies. Furthermore, where training is not perfectly general, even where it might be agreed that employers and employees are likely to share the cost of training, there is no accepted theory of how the cost of training will be shared between the two. In the face of this theoretical agnosticism, we stick with the simple assumption that the employer appears to pay for training through lost output, and that workers – perhaps unable fully to unravel the intertemporal workings of the game – simply accept the highest current wage they are offered, without seeking to buy preferential access to training.

The third issue, closely related to the second, is whether workers simply accept whatever is the highest current wage offer, or whether they take account of the present value of wage-earning opportunities associated with a particular choice. In real life, training opportunities matter to workers as well as the current wage offered. In real life, workers might be reluctant to leave the source firm – even if the source firm does not offer the highest current wage – because it is the technological leader, and leaving its employment may cut off future opportunities for training and advancement. In this model, when T occurs in period 1, the workers who accept the host firm's wage offer in that period do not receive training, and so might receive lower wage earnings in period 2. It would be highly desirable to incorporate this issue into the model, but in the interest of simplicity I have not so far done so; this is a topic for future research.

The fourth issue is the following: it has been implicitly assumed here that a host firm employs a skilled worker recruited from the source firm solely in production and not as a trainer of other workers. This strong assumption implies that if the host firm recruits even one newly trained worker from the source firm, it will replace its entire work force with such workers. Realistically, however, host firms in developing countries often seek to hire just one or a few such workers in supervisory roles, as trainers, and doing so may well imply a higher benefit/cost ratio for the host firm. An interesting question is whether allowing the host firm to hire newly trained workers as trainers in the model would make technology transfer more likely or less likely.

IV. Conclusion

Technology transfer to developing countries is often thought of as occurring through movement of trained skilled workers from multinational subsidiaries to local firms. However, some recent careful empirical studies find a lack of technology transfer from FDI to local firms in the same sector. Moreover, the substantial wage premium paid to skilled workers in multinationals relative to local firms suggests that it would be surprising if many workers did move to local firms if they had the opportunity to stay in multinationals. Given these empirical findings, it is desirable to construct a model in which several realistic determinants of technology transfer through movement of skilled workers among firms are analyzed, and in which technology occurs for some parameter values and not others. This has been done here, in a model which incorporates some relevant features not present in earlier models such as Glass-Saggi (1999).

The two-period model presented here, with costly and time-consuming training, seeks to capture the effects of several determinants of the wages offered to trained workers by source and host firms, and hence of how much technology transfer occurs. The results are similar but not identical to those of Glass and Saggi (1999) in a static model with costless and instantaneous training. For linear demand, they find that for linear demand, technology transfer takes place for a region of the parameter space that depends only on the transferability of training from the source to the host firm. (The productivity of trained workers need only exceed that of untrained workers, but otherwise the productivity of untrained workers does not affect the outcome.) In contrast, I find that whether technology transfer occurs depends on the size of (Q - q), the gap in the host firm between trained and untrained workers' unit labor cost, relative to (q – 1), the increase in trained workers' unit labor cost upon moving to the host firm. Further, technology transfer is more likely to occur when upgrading to new technology brings a large gain in best-practice productivity and/or when skill is highly transferable from one vintage of technology to the next.

In the interest of simplicity, the model presented here has left out several features that may well be important in a full theory of technology transfer through movement of skilled workers among firms. Some of these have been briefly discussed, and suggest promising avenues for future research.

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