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A Theory of Worker Turnover and Knowledge Transfer in High-Technology Industries

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This paper builds a theoretical model to address evidence on labor mobility patterns in high-technology firms engaged in R&D. Worker turnover in these industries enables the efficient transfer of R&D knowledge across firms in a production environment characterized by volatile returns to R&D investment. We show that both the size and composition of labor turnover are affected by the extent to which R&D knowledge can be transferred and applied across the production processes of different firms. Our analysis also provides implications of such labor mobility for industry growth. We explain how labor turnover in the presence of knowledge transfer has contributed to the success of the high-technology cluster in Silicon Valley.

I. Introduction

Labor markets in high-technology industries have been the focus of considerable academic research because of the unique nature of employment relationships among such firms. Many studies have pointed to significant differences in labor market outcomes in these industries.

The first distinguishing feature is the persistence of substantial employee turnover. Over the decades, high-technology clusters have experienced significantly higher rates of turnover than other industries. "Job hopping" is a common phenomenon in Silicon Valley, and firms have consistently experienced turnover rates upward of 20 percent, which is more than twice the national average (Joint Venture 1999).

Second, empirical and anecdotal evidence suggests that the composition of worker turnover is different in these industries than in other indus-

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tries. In particular, high-ability workers switch employment often, while less productive workers do not. Studies in the organizational sciences suggest that worker turnover is perceived as a positive signal by employers, and in contrast to traditional labor markets, there appears to be no stigma attached to a worker moving from one firm to another.[1] Evidence of a positive selection of high-ability workers in the turnover pool is also suggested by wage increases experienced by job changers in high-technology labor markets (Morgan, Campione, and Jerrell 2004). Further, research on engineers and technology workers has found that in many instances, turnover is not negatively correlated with tenure as most traditional theories would suggest. Technology firms appear to be increasingly relying on the external labor market for filling not only entry-level positions but more senior-level positions as well, and there is much less reliance on performance incentives in which employers select workers with longer tenures for career development and promotions (Josefek and Kauffman 2003; Joseph et al. 2007; Andersson et al. 2008). As a result, the turnover pool often comprises workers with substantial tenure in their previous employment.

Finally, labor turnover and the consequent transfer of technical knowledge have played an important role in the success of many high-technology clusters, most notably in Silicon Valley. Thus, while labor turnover has traditionally been viewed as a drag on industry growth because of the loss of specific human capital, high-technology industries appear to have greatly benefited from it. Several studies have emphasized the importance of labor mobility in enabling the free flow of R&D knowledge across Silicon Valley firms. In contrast, the decline of firms in the Route 128 industrial cluster of Massachusetts has been attributed to excessive restrictions placed on employee mobility (Saxenian 1994; Gilson 1999; Hyde 2003).

In this paper, we develop a theoretical model to explain these three distinguishing features of high-technology labor markets, namely, (a) the persistence of high levels of employee turnover, (b) the predominance of highly productive employees in this turnover pool, and (c) the positive impact of labor turnover on the growth of the high-technology industry. We argue that these labor turnover patterns emerge from two important functions served by labor mobility in these industries. First, worker turnover acts as a conduit for transferring R&D knowledge across firms and hence can improve the utilization of this knowledge in the industry.[2] Second, technological innovations are very large but also highly volatile. The resulting persistence of firm-specific technological shocks creates a continuous cross section of expanding and contracting firms in the in-

[1] Interviews with engineers and employers in Silicon Valley strongly suggest that employees who change jobs often are perceived as enterprising and talented, while employees who stay in the same firm for too long risk acquiring a reputation as "deadwood" (Saxenian 1994; "Tech Employees Jumping Jobs Faster," CNET News.com, June 14, 2000).

[2] Numerous studies have established that the mobility of technical workers is a source of R&D knowledge transfer across technology firms. See, e.g., Almeida and Kogut (1999) and Moen (2005).

dustry. Labor mobility then facilitates the reallocation of talent and resources toward firms with superior innovations, thus leading to a more efficient allocation of worker productivities across firms (see Bailyn 1991; Fallick, Fleischman, and Rebitzer 2006).

Our theoretical model builds on the standard analyses of asymmetric employer learning with job assignments.[3] We incorporate stochastic returns on R&D investment and R&D knowledge accumulation and transfer across firms into this framework. The model generates a number of interesting results. First, we explain the persistence and composition of labor turnover in high-technology labor markets. When workers are assigned to technically challenging R&D projects within their firm, they acquire substantial access to critical R&D knowledge, which they can then transmit to other firms if they switch employers in the future. Since output in these R&D projects is also likely to be more sensitive to worker ability, higher-ability workers are assigned to such jobs. If this firm suffers a negative technology shock, it will have a pool of highly productive workers who have accumulated R&D knowledge but are more productive in a new firm with a superior technology. The resulting misallocation of worker productivities across firms makes turnover of high-ability R&D workers efficient in our model. When such turnover is realized as the equilibrium outcome, we refer to it as “complete turnover” of R&D workers in the secondhand labor market. We show that when returns from R&D investment are highly variable and R&D knowledge is easily substitutable across firms, we observe complete turnover of high-ability R&D workers.

We also provide a framework for explaining why high-technology industries have moved away from traditional tenure-based promotion rules toward greater reliance on the external labor market even at higher levels of the job ladder. R&D knowledge accumulation occurs with tenure in the firm. However, technology shocks can occur at any point during the worker’s tenure. Thus we find that, in the event of a negative technology shock in the current firm, workers with longer tenure may be more productive in a new firm.

Finally, we describe when and why labor mobility can enhance industry output. The relationship between worker turnover and industry output is driven by two counteracting effects: the incentive for firms to invest in R&D decreases with greater worker turnover as firms cannot appropriate all the gains from their investment; but on the positive side, worker turnover improves the allocation of worker productivities across firms. We show that when R&D knowledge transfer across firms is significant, as in the case of high-technology industries, the net effect of worker turnover on industry output is positive.

The paper is structured as follows. In Section II, we describe our contribution to the literature on labor turnover and knowledge transfer. Sec-

[3] See Waldman (1984) and Ricart i Costa (1988) for standard models of asymmetric learning with job assignments.

tion III provides details of the theoretical model. Section IV describes the equilibrium and efficient outcomes for job assignment, turnover, and investment and the impact of turnover on industry output. Section V concludes our analysis by providing a general discussion of our results as they apply across other industries outside high technology. All proofs are in the Appendix.

II. Related Literature

Our analysis adds to the growing literature on knowledge transfer through labor mobility in high-technology labor markets. Prominent work in this area has been in the field of organizational sciences and legal studies. Saxenian (1994) provides a vivid contrast of the experience of Silicon Valley and Route 128. Using anecdotal evidence on the labor market experience of engineers in Silicon Valley, she highlights the importance of labor turnover and knowledge diffusion by employees across firms. Legal scholars such as Gilson (1999) and Hyde (2003) discuss how favorable labor laws surrounding trade secret protection and noncompete clauses contributed to the growth of Silicon Valley. On the other hand, research on the importance of knowledge transfer in high-technology labor markets is much less abundant in the economics literature. Economic research in this area has mainly focused on the role of knowledge flows, labor pooling, and labor market competition in the formation of industrial clusters (Duranton and Puga 2004; Combes and Duranton 2006; Gerlach, Ronde, and Stahl 2009). As in these papers, we also consider labor market competition when workers transfer knowledge across firms through mobility. However, our focus is on the implications of such knowledge transfer for the composition of labor turnover and its impact on industry output. To our knowledge, there is an absence of economic theory linking knowledge transfer through worker mobility to observed labor market outcomes in the high-technology sector. Our paper attempts to fill this gap.

We also address shortcomings of the existing theories of labor turnover in analyzing high-technology labor markets. The literature in labor economics has typically addressed worker turnover in two ways. One stream of research has treated labor turnover as exogenous and explored patterns of wage, tenure, and promotion as well as human capital formation in this framework. Much of this literature has used asymmetric learning in the labor market to predict adverse selection in the turnover pool (Greenwald 1986; Gibbons and Katz 1991). However, since these studies assume exogenous worker turnover, they fail to explain the persistence of labor turnover in high-technology industries. Also, while many empirical studies have confirmed the presence of asymmetric learning in labor markets in general and in the market for engineers in particular, there is strong evidence to suggest that the “marking effect” emphasized in the adverse selection literature, where a worker’s perceived ability decreases with each move to a new firm, does not exist or is mitigated by other positive factors enabling mobility in high-technology labor markets.[4] In contrast to these studies, our paper explains the persistence of worker turnover in high-technology industries and, by incorporating job assignment decisions with respect to R&D-intensive jobs, allows us to explain the predominance of highly productive workers in the turnover pool.

A second approach in the literature explains turnover decisions endogenously as we do in this paper. Existing economic models use heterogeneous firm-worker matches and search-theoretic models of employment to explain observed turnover (Burdett 1978; Jovanovic 1979; Mortensen and Pissarides 1999; Rogerson, Shimer, and Wright 2005). However, none of these models adequately explain the absence of a negative correlation between worker turnover and tenure found in high-technology labor markets. In matching models, as the quality of the firm-worker match is revealed over time, separations occur when the match quality is lower than the average expected quality in the labor market. But once the true match quality is revealed to be high, the possibility of turnover no longer exists for the worker. A key contribution of our model is that we introduce temporal variability in firm-worker matches and we argue that the true firm-worker match quality itself may change over time depending on the stochastic realization of technology. This breaks the link between tenure and turnover. Some search-theoretic models, such as the one described by Coles and Mortensen (2011), also allow stochastic productivity shocks at the firm level to generate efficient turnover in a manner similar to ours. However, these models do not account for differences in worker productivity that influence the characteristics of turnover as we do in the current paper. This is important for two reasons. First, it allows us to draw a relationship between job assignments, knowledge accumulation, and turnover. Second, it also allows us to capture the impact of turnover on overall industry growth through its effect on the firm's job assignment and investment decisions.

III. Model

There is free entry into production, where all firms are ex ante identical and the only input is labor. A worker's career lasts three periods. In each period, the worker supplies one unit of labor inelastically. There are an infinite number of firms in the market. There are two job levels in the production hierarchy of firms: job level 1 and job level 2. Job level 2 involves working with technically challenging R&D projects, the returns to which are stochastic.

[4] A recent paper by Kahn (2012) finds a stronger presence of asymmetric learning in occupations such as computer programmers, researchers, and technicians than among workers in professional service industries such as consultants, lawyers, accountants, health care givers, etc. See also DeVaro and Waldman (2012).

In the first period, firms hire workers. We denote the ability of workers as θ, which varies uniformly over the interval $[0, 1]$. Firms and workers cannot observe θ. After the worker has been employed in the firm for more than one period, her ability becomes known to her current employer. At the end of the first period, firms invest $I \in [0, \bar{I}]$ in R&D. There is an increasing and convex cost function for R&D investment denoted by $c(I)$, with $c(0) = 0$, $c'(0) = 0$, and $\lim_{I \to \bar{I}} c'(I) = \infty$.

In every period following the investment, there is an exogenous probability, $p \in (0, 1)$, that the firm's technology is successful.[5] Let r_{it} denote the returns to R&D investment. When firm i's technology is successful, $r_{it} = r > 0$, while $r_{it} = 0$ when it is unsuccessful. The probability, p, of a successful draw in any period is independent of the outcome in the previous period.

Without loss of generality, we refer to the current employer firm as i and a new employer as j. The productivity of a worker in job level 1 is independent of her ability. For a worker who has been employed in firm i for τ periods, her output in job level 1 is

$$y_i^1 = 1 + s_\tau,$$

where $s_\tau = 0$ for $\tau = 0$ and $s_\tau = s > 0$ for $\tau > 0$. That is, a worker who has been in a firm for more than one period accumulates firm-specific human capital of s, which enhances her productivity in the current firm.

The output of worker k assigned to job level 2 in her current employment in period t is

$$y_{itk}^2 = \theta_k (1 + s)(r_{it} + r_{it-1}) I,$$

where $r_{it} \in \{0, r\}$ is the returns to R&D investment in period t. Note that while worker output in job level 1 is constant, in job level 2 her output depends on ability. This means that the firm assigns relatively higher-ability workers to job level 2 while keeping lower-ability workers in job level 1.[6]

For worker k from firm i, output in job level 2 in a new firm j in period t is

$$y_{jtk}^2 = \theta_k (r_{jt} + \beta r_{it-1}) I,$$

where β denotes the extent to which R&D knowledge acquired by the worker in job level 2 is substitutable across firms. We assume that $\beta \in [0, 1]$ so that current employers with successful technology can utilize

[5] We implicitly assume that there are an infinite number of firms in the industry. This ensures that there is always at least one firm that has a good return on its investment in any period. The reason is that the probability that all firms have zero returns on investment goes to zero. If n is the number of firms, $\lim_{n \to \infty} (1 - p)^n = 0$.

[6] Our results do not depend on the assumption that job level 1 output is independent of ability and investment. We could consider a more general specification in which job level 1 output is $[1 + \lambda\theta(r_{it} + r_{it-1})I](1 + s_\tau)$, with $\lambda < 1$. For $\lambda = 0$, we are back to our original model. All our results hold as long as we assume that λ is small enough.

their workers' research experience better than a new firm.[7] Note that there is some continuity in the utilization of past technology. The idea is that even if $r_{i3} = 0$ and the old technology used by the firm declines, the utilization of that technology in the firm's production process does not disappear abruptly; rather it continues to be used in future periods. Hence the knowledge gained from working with a technology in period 2 can be applied to production in subsequent periods even if the firm experiences an adverse investment shock and the firm's technology declines in period 3. Similarly, if the old technology declines, the R&D knowledge associated with that technology can be applied toward a new technology in a new firm, but in a less than perfect way (so that $\beta \leq 1$). This allows us to examine cross-period interactions between job assignments and turnover.

We assume that the average worker is always more productive in job level 1 in period 2, that is, $\frac{1}{2}r\bar{I} < 1$. This also ensures that a worker about whom the firm has no information is assigned to job level 1. Finally, we assume that the cost of investment is convex enough so that the firm's profit function is concave.[8]

The timing of events is as follows. In the first period, firms hire workers. Worker ability is unknown to all firms and workers, although they know the distribution of abilities. Since a worker does not produce any output in job level 2 in the absence of R&D investment, all workers are assigned to job level 1 in period 1. At the end of period 1, firms invest in R&D. Firms' investment levels are publicly observable. Worker ability is privately revealed to the current employer but is unknown to new employers in the outside market. In the beginning of period 2, the firms' R&D outcome is realized, and it is observed by all firms and workers. Firms announce job assignments for each of their workers. The outside market makes wage offers to new workers based on observed job assignments and turnover.[9] Each firm can make counteroffers to workers whom it wishes to retain. Workers accept the highest wage offer and stay with the same firm if indifferent. The same sequence of events as in period 2 repeats in period 3. After period 3, the game ends.

IV. Analysis

We solve for the outcome of this model by backward induction in this section. The solution concept used is perfect Bayesian equilibrium.

[7] See Moen (2005) for an empirical justification of this assumption.

[8] A sufficient condition to ensure concavity of the profit function is $3(1+s)(1/rI^3) < c''(I)$ for all $I \in [1/r, \bar{I}]$. Details are provided in the Appendix.

[9] We do not need to make any assumptions about a worker's information about her own ability. Even if the worker knows her ability as the current employer does in period 2, there is no way for her to credibly communicate that to a new employer. In other words, every worker wants to pretend to have the highest ability, and knowing that, new employers simply ignore any communication from the worker about her ability. They instead condition their beliefs on observed job assignments and turnover.

A. *Job Assignments and Turnover*

In order to derive the job assignment and turnover outcomes for periods 2 and 3, we take as given the symmetric equilibrium investment of firms in period 1, I^*. Later we derive the equilibrium investment explicitly. We represent the R&D outcome history of firm i in period 3 by the tuple (r_{i2}, r_{i3}), where each takes the value of r or zero depending on whether firm i's technology was successful or not in periods 2 and 3, respectively. Thus, a firm with history (r, r) had successful outcomes in both periods. History $(r, 0)$ means that the firm had a positive return in period 2 but not in period 3. The four possible histories that a firm can have in period 3 are (r, r), $(r, 0)$, $(0, r)$, and $(0, 0)$. Also, we refer to workers who have worked in a job level 2 position in a firm that had successful investment returns as "R&D workers."

Turnover of workers can occur only if worker productivity is higher in a new firm. In firms with history (r, r) and $(0, r)$, the worker is always more productive in the current employment because of better internal utilization of research experience and the firm-specific human capital accumulated by the worker. Hence turnover never occurs in these two cases. In the case in which a firm has history $(0, 0)$, turnover does not occur simply because the firm does not have an incentive to assign any worker to job level 2 in either period and a worker with no R&D experience is always more productive with her original employer. So turnover can occur only in the case in which a firm's technology was successful in period 2 but declined in period 3, that is, in firms with history $(r, 0)$. In such firms, workers may be more productive in another firm if the R&D knowledge they can transfer is high enough. Since we are interested in considering all possible ranges of β in which promoted workers are more productive in a new firm, we assume that firm-specific human capital is low enough to allow these situations to arise. A sufficient condition to ensure this is $s < 1$. Proposition 1 establishes the conditions under which turnover occurs.

Proposition 1. Given the possible histories of R&D realizations, turnover occurs in period 3 if and only if a firm has R&D outcome history $(r, 0)$ and $\beta \geq s$.

In order to focus on the nature of worker turnover in these firms, for the rest of the analysis in this paper, we restrict attention to the case in which turnover occurs in period 3, that is, firms that have R&D outcome history $(r, 0)$ with $\beta > s$. We further assume that $\frac{1}{2} \leq p \leq 1$ to ensure that promoted workers are paid a higher retention wage than job level 1 workers in period 2. We also restrict $I^* > 1/r$ so that a positive measure of workers is promoted in firms with successful technology in period 2.[10]

Proposition 2 describes some features of the equilibrium outcome for periods 2 and 3 in a firm with R&D outcome history $(r, 0)$.

[10] Under our restrictions on the cost function, this is true for the equilibrium level of investment. This is shown in the proof of proposition 3 in the Appendix.

Proposition 2. For a firm with R&D history $(r, 0)$ and investment $I^* > 1/r$, the equilibrium outcome in periods 2 and 3 has the following properties:

a. In period 3, there exists $\hat{\theta}_3 \in [1/rI^*, 1]$ such that workers with $\theta \leq 1/rI^*$ are retained in job level 1, those with $1/rI^* < \theta < \hat{\theta}_3$ move to a new firm, and those with $\theta \geq \hat{\theta}_3$ are retained in job level 2.
b. The average wage of workers who turn over in period 3 is greater than the wage for retained workers if and only if β is high enough.
c. The proportion of workers who turn over in period 3 is decreasing in I^*.
d. In period 2, all workers are retained in the same firm and a worker with ability θ is assigned to job level 2 if and only if $\theta \geq 1/rI^*$.

Proposition 2 yields a number of insights about the size and composition of labor turnover in these firms. First, note that in period 3 for firms with history $(r, 0)$, it is not the lowest-ability workers who are moving to new firms. Since a firm assigns higher-ability workers to job level 2 in period 2, these workers gain R&D experience that can be more productively utilized in a new firm if the current firm's technology suffered a negative shock.[11] In fact, contrary to the predictions of existing asymmetric learning models, the lowest-ability workers are least likely to change firms. Also, if R&D knowledge is easily substitutable across firms, the retention wage for R&D workers is high, making it costly for the firm to retain these workers. This leads to greater turnover.

Part *b* of the proposition states that when knowledge is easily transferable, retained workers earn a lower wage on average than workers in the turnover pool. This conforms to evidence of wage increases experienced by job changers in high-technology labor markets. Morgan et al. (2004) find that job changers in information technology (IT) occupations earn about 5 percent more than those who do not change jobs. Conversely, this wage effect is absent in non-IT occupations.

Part *c* shows that investment and turnover are negatively correlated. As I^* increases, the profit from retaining a worker with R&D experience in the current employment is higher. As a result, more workers are retained and turnover is lower. In a study of Norwegian high-technology firms, Moen (2005) finds that turnover is lower when R&D investment is higher. Our model captures this negative dependence of R&D investment on turnover.[12]

[11] This result is similar to that of Perri (1995), who shows that the winner's curse phenomenon that arises when a firm can make counteroffers disappears when job assignments signal ability and there is some exogenous turnover.

[12] The only other paper to our knowledge that models R&D investment in the presence of spillovers via worker mobility is Cooper (2001). Cooper considers a model in which competing firms invest in R&D and workers can switch employers in the event of a bad match with the current employer. When the worker does so, she is able to utilize a part of the R&D investment from her previous employment in the new firm. Thus worker mobility helps to internalize spillovers, and this mitigates the overinvestment inefficiency caused by

Part *d* states that there is no turnover in any firm in period 2. Turnover occurs only in period 3 after a measure of workers have acquired R&D knowledge from being employed in R&D-intensive jobs in period 2. This provides an explanation for the absence of a negative relationship between tenure and turnover. Since promotions to job level 2 occur in the later part of the worker's career and R&D knowledge that determines her productivity in a new firm is tied to promotions, turnover does not decrease with tenure.

In the first period, all firms are identical with respect to the information they have concerning worker abilities. Owing to competition for workers in the external labor market, firms make zero profits and all workers are paid their output in period 1 plus the total expected profits they generate for the firm in periods 2 and 3. Since all workers are assigned to job level 1 by assumption, the expected output from a worker in period 1 is 1. If the expected profit from a worker in periods 2 and 3 is given by $\pi(I^*)$, then the first-period wage is $w_1 = 1 + \pi(I^*)$.

B. Investment in R&D

In this subsection we derive the equilibrium R&D investment in period 1. Given the structure we have imposed on costs, the R&D investment chosen by firms is high enough to make it worthwhile to assign a positive measure of workers to job level 2 if the firm has a successful technology in any period. Let $\pi^{r_2 r_3}$ denote the expected profit across periods 2 and 3 from a worker if the realized R&D outcome is (r_2, r_3). Then, the total expected profit from investing I in R&D in period 1 is

$$\begin{aligned}\pi(I) = {} & (1-p)^2\pi^{00}(I) + p(1-p)[\pi^{0r}(I) + \pi^{r0}(I)] \\ & + p^2\pi^{rr}(I) - c(I).\end{aligned}$$

In the following proposition we compare the equilibrium level of investment and promotion with the efficient level.

Proposition 3. The equilibrium levels of investment and job assignment are inefficient, and this inefficiency increases as β increases.

Period 2 job assignments are inefficient in firms that had successful technology that period because assigning a worker to the R&D job allows her to accumulate R&D knowledge and hence raises her productivity in all firms. This drives up her retention wage and depresses the

R&D spillovers. Cooper's model predicts that worker mobility will not depend on the level of R&D investment. By contrast, we are able to generate the dependence between turnover and investment found by Moen by incorporating the interaction between investment, job assignments, and knowledge accumulation. Firms always have the option of assigning a worker to a lower-level job in which there is no opportunity for R&D knowledge accumulation and possible turnover. But the loss from misassigning a worker to prevent turnover is directly influenced by the level of investment in the firm.

firm's incentive to promote her to the R&D job even if she is more productive with the promotion. The same holds true for equilibrium investment as well.

Note that the substitutability of R&D knowledge across firms, represented by β, has a positive effect on the efficient investment level in the industry since it increases the productivity of R&D workers in period 3. On the other hand, higher levels of β lower the investment level chosen by firms. Hence, as β increases, the difference between the efficient investment level and the equilibrium level widens. Now as the firm's investment level falls as β increases, fewer workers are assigned to R&D jobs. On the other hand, efficiency requires that more workers should be assigned to job level 2, both because of a direct effect on output of an increase in β and also because of the consequent increase in the efficient investment level in period 1. This means that the efficient and equilibrium promotion cutoffs also diverge as β increases.

The effect of knowledge transfer on the promotion cutoff provides an interesting result concerning the relationship between β and the average ability of the turnover pool in period 3. This is formalized in the following proposition.

Proposition 4. The average ability of a worker from a firm with R&D outcome history $(r, 0)$ who changes employers in period 3 increases as β increases.

As explained above, equilibrium investment decreases as β increases. The lower investment implies a lower profit from assigning workers to job level 2 in period 2, and hence $\hat{\theta}_2$ increases. At the same time, as β increases, the cutoff ability level of the worker who changes employment increases; that is, $\hat{\theta}_3$ increases. Thus, as R&D knowledge becomes more substitutable across firms, the average ability of workers who switch jobs increases.

C. *Turnover Efficiency and Complete Turnover of R&D Workers*

Asymmetric information about worker abilities in the presence of knowledge transfer also leads to inefficiently low levels of turnover in equilibrium. Specifically, consider the outcome in firms with R&D history $(r, 0)$ in period 3. All workers with R&D knowledge from such firms are more productive in a firm that has successful R&D returns in period 3. Hence efficient turnover means that all R&D workers in these firms with $r_{i3} = 0$ move to a new firm. In the following analysis, we look at conditions that lead to turnover of all R&D workers in period 3.

The nature of the relationship between knowledge transfer, turnover, and investment highlighted in propositions 3 and 4 suggests that for β high enough, firms that realize R&D outcome $(r, 0)$ in period 3 may not find it profitable to retain any R&D worker. In this case, all workers with $\theta \geq 1/rI^*$ switch employment to a new firm, leading to complete turnover of all R&D workers. In other words, given the level of investment and the set of workers who are promoted, the allocation of workers across firms in period 3 is efficient.[13]

Under our assumptions, the highest level of β is 1, implying that R&D knowledge is perfectly substitutable across different firms. Let $\hat{I}$ represent the lowest level of investment such that a firm with history $(r, 0)$ finds it profitable to retain a positive measure of workers with R&D experience even when $\beta = 1$. The following proposition formalizes the conditions under which $I^* \leq \hat{I}$.

Proposition 5. In period 3, there is complete turnover of all high-ability R&D workers if the following conditions hold:

a. β is high relative to s, and
b. p is neither too high nor too low.

The above proposition emphasizes the impact of knowledge transfer and investment volatility on the composition of worker productivity in the turnover pool. When β is high, the wage that needs to be paid to retain workers with R&D experience in firms that have outcome $(r, 0)$ is greater than their productivity in the firm. Thus, all high-ability workers with R&D experience turn over. The intuition for why variability in returns to investment is important for complete turnover of R&D workers is as follows. Consider a situation in which p is too high, so that the equilibrium level of investment in period 1 is very high. When this is the case, a firm with R&D history $(r, 0)$ in period 3 retains some of its workers with R&D experience. On the other hand, if p is too low and hence investment is very low, firms with successful returns in period 2 do not find it profitable to assign any worker to the R&D-intensive job. In this case, no worker has R&D experience, which means that turnover does not occur in period 3. Thus, complete turnover of R&D workers is observed when p is high enough so that it is profitable to assign workers to the R&D job in period 2, but p is not high enough to induce large investments that make it profitable to retain R&D workers in period 3 if R&D returns are zero. Intermediate values of p in turn correspond to high variance in R&D returns. Since high-technology industries frequently consist of numerous small firms, especially start-ups, with greater unpredictability in returns from innovation, the predictions from proposition 5 provide an explanation for the predominance of high-ability workers in the labor turnover pool.

There has been much discussion in the literature on job hopping in technology industries about how easy mobility has facilitated the success of this industry. In particular, many researchers have discussed the role of labor mobility in the differing experience of the Route 128 technology firms in Massachusetts and the industrial cluster in Silicon Valley.

[13] Note that the allocation of workers across firms is still inefficient in period 2. For example, high-ability workers in firms with $r_{i2} = 0$ should be assigned to job level 2 positions in firms that have $r_{i2} = r$.

Saxenian (1994) identifies cultural differences as explaining the variation in labor mobility across the two clusters, while Gilson (1999) and Hyde (2003) point to differences in the legal infrastructure and in particular the unenforceability of noncompete clauses and ineffective trade secret laws in California. At the same time, there is also a vast literature that looks at the formation of industrial clusters especially in high-technology industries. These papers identify the importance of labor pooling as a factor driving competing firms to locate close to each other (Fosfuri and Ronde 2004; Combes and Duranton 2006; Gerlach et al. 2009).

While examining the reasons that lead to the easy movement of labor in Silicon Valley and other high-technology clusters is beyond the scope of this paper, we can use our framework to describe when and why labor mobility facilitates industry growth. Our model predicts that this is more likely to be the case when we have complete turnover of high-ability R&D workers under the conditions described in proposition 5. Let us denote the cutoff level $\tilde{\beta} \in [s, 1]$ as the level of β identified by proposition 5 above which there is complete turnover of R&D workers in period 3. Let δ_1 and δ_2, $\delta_1 < \delta_2$, denote the level of restrictions to labor mobility in two otherwise identical industries (or technology clusters). We can think of industry 1 as the Silicon Valley cluster and industry 2 as the Route 128 firms and δ as the level of trade secret protection enforced by state law. Then the effective level of R&D knowledge transfer possible across firms in industry $k \in \{1, 2\}$ is given by $\beta - \delta_k$. Let Y_k^* denote the total expected equilibrium output in industry k across all periods.

Proposition 6.

a. When there is complete turnover of all R&D workers in the turnover pool in period 3, that is, $\beta - \delta_k \geq \tilde{\beta}$ for every k, greater restrictions on labor mobility lower industry output so that $Y_1^* \geq Y_2^*$.

b. In the absence of complete turnover in period 3, that is, if $\beta - \delta_k < \tilde{\beta}$ for any k, the effect of labor mobility restrictions is ambiguous and $Y_1^* \gtrless Y_2^*$.

Before we explain part *a* of the above proposition, it is useful to understand the output effect of δ_k when $\hat{\theta}_3 < 1$ and the $(r, 0)$ firms retain some of their R&D workers in period 3. In this case, labor market restrictions affect the firm's investment choice in period 1. The reason is that with a higher δ_k and consequently a lower $\beta - \delta_k$, the firm expects lower turnover and hence higher profits from its R&D workers in period 3. Since the firm can appropriate more of its investment from R&D workers, $dI^*/d\delta_k > 0$. This investment effect tends to increase industry output. On the other hand, lower turnover also means greater turnover inefficiency, which dampens industry output. Without making additional restrictions on the parameters and the investment cost function, it is not possible to say which of these effects is stronger.

However, when all R&D workers move to a new firm, the investment effect of labor mobility restrictions disappears. The reason is that with all job level 2 workers leaving the firm in period 3 with an $(r, 0)$ outcome history, the firm does not expect any profits from its R&D workers in that event. Then the only effect of labor mobility restrictions is that it reduces the utilization of R&D knowledge by a worker in a new firm and hence necessarily lowers industry output.

Proposition 6 provides a possible explanation for why the high-technology industry in Silicon Valley appears to have outperformed that in Route 128. The extensive use of noncompete contracts and trade secret protection facilitated by permissive Massachusetts law restricted labor mobility between Route 128 firms and may have hindered the efficient allocation of highly productive technology workers across firms in that cluster.

At the same time our results also provide caution against blanket recommendations in favor of labor mobility. In particular, we find that industry dynamics in terms of investment volatility and knowledge transmission across firms play an important role in determining the appropriate level of labor mobility for an industry. To our knowledge, most of the studies that have examined the effect of legal restrictions on labor mobility focus only on high-technology industries (Marx, Strumsky, and Fleming 2009; Samila and Sorenson 2011). As our results suggest, high-technology industries are likely to experience both very high rates of turnover among productive workers and positive industry outcomes resulting from such turnover. Both these features are driven by underlying industry characteristics, namely, the volatile nature of investment in technology and the transfer of R&D knowledge across firms through worker mobility. By restricting the analysis to high-technology industries, existing studies do not capture crucial industry-specific factors that influence the relationship between labor mobility and industry growth. Thus, our analysis calls for cross-industry comparisons of the effects of labor mobility restrictions accounting for specific industry characteristics that affect labor turnover there.

V. Discussion and Conclusion

In the current section we discuss our results more broadly and draw a contrast between the experience of the high-technology industry and that of other knowledge-creating industries as well as other industries in which firms experience worker turnover as a result of stochastic productivity shocks.

There is a wide range of professional service industries that one could classify as knowledge-intensive, such as law and accounting firms, financial service firms, and consulting firms. As with high-technology firms, employees in such occupations embody a great deal of knowledge acquired through their work experience in the current employment. However, these markets generally face relatively stable demand as well as more or less standardized production processes. While these firms may be subject to industrywide macroeconomic shocks that displace workers from time to time, they do not experience continuous and firm-specific investment shocks in a manner in which high-technology firms do. As a result, most of these firms appear to have strong internal labor markets or up-or-out promotion ladders with low overall turnover rates.[14]

Several industries, apart from high-technology markets, experience volatile demand or supply shocks that cause some firms within the industry to expand and others to contract. Anderson and Meyer (1994) show that there is significant job turnover caused by simultaneously expanding and contracting firms in manufacturing and retail. However, in contrast to high-technology markets, turnover imposes significant costs on firms and workers. In both manufacturing and other sectors, such as retail trade and services, that have high separation rates, there are significant earnings losses for workers and rehiring costs for firms as a result of turnover. Further, much of the turnover in the manufacturing sector results from temporary separations in which the worker returns to the employer after a period of time. This points to the importance of firm-specific human capital in such industries and a limited role for knowledge transfer.

Finally, we note that even within the high-technology industry, there is some variation in the volatility of investment and the extent of labor mobility. While we have referred to high-technology industry and R&D-intensive firms as a homogeneous block, it is important to look at disaggregated subsectors to correctly apply our results. For example, Fallick et al. (2006) note that while the computer industry clusters in California exhibited significantly higher rates of job hopping than similar clusters in other states, these differences were not significant outside the computer industry. As these authors point out, this is likely the result of the modular production style adopted by the computer industry that exposes these firms to greater technology shocks than other industries.[15] This again confirms our hypothesis about the nature of labor turnover being driven by volatility in investment returns.

Our analysis provides some useful directions for future empirical study of labor turnover. In spite of an abundance of case studies and interview-based studies of high-technology firms in the organizational science and sociology literature, there have been few systematic empirical studies of the patterns of turnover or its effects on industry growth in the R&D-

[14] For example, studies of financial firms, most notably Baker, Gibbs, and Holmstrom's (2001) single-firm study, establish the presence of strong internal labor markets in such firms (see also Eriksson and Werwatz 2005). To be sure, the Baker et al. study does find external hiring at all job levels within the firm. There is a general view among many labor economists that firms in several industries are moving to a greater dependence on external markets and spot wage determination. However, internal labor markets appear to have shown a greater decline in high-technology industries than in other sectors (DiPrete, Goux, and Maurin 2002; Osterman and Burton 2005).

[15] Modular production means that computer manufacturers rely on independent suppliers for individual components. Since these suppliers pursue their own innovation strategies, the rate of technical advancement in the computer industry is quite high.

intensive technology sector. Fallick et al. (2006) provide a good analysis of the reasons driving high labor mobility in Silicon Valley. The results of their study conform to a number of assertions brought out by our model. At the same time, their results suggest that there are unique aspects of the computer industry that interact with the legal environment in California to make job hopping so common. In light of their findings and our own, we believe that it is important to examine the effect of industry-level characteristics, such as R&D investment, technological volatility, and the importance of knowledge transfer on turnover and industry output. Policies that facilitate or restrict the movement of labor across firms are likely to have different implications for an industry depending on the importance of knowledge transfer via labor turnover in that particular industry. This calls for further empirical study of the effects of labor mobility on industry growth controlling for the underlying industry-level characteristics that influence the patterns of such labor turnover.

Appendix

Proofs of Propositions 1 and 2

We present the proofs of propositions 1 and 2 together since they are related. We first derive the equilibrium in period 3 and then work backward. Before that, we solve the cutoff β as given in proposition 1. In firms with R&D outcome history (r, r), all workers are more productive in their current employment in both periods. Hence, there is no worker turnover from such firms in equilibrium. In firms with R&D history $r_{i2} = 0$, no turnover occurs since all workers are assigned to job level 1 in period 2, and no new firm is willing to assign a completely unknown worker to job level 2 given our assumption that $\frac{1}{2} r\bar{I} < 1$. Hence, turnover can occur only if a firm has outcome history $(r, 0)$, and workers who accumulated research experience from holding job level 2 positions in that firm are more productive in a new firm that has a good R&D draw in period 3. This happens when $\theta(1 + s)rI^* \leq \theta(1 + \beta)rI^*$, which means that $\beta \geq s$.

When $\beta \geq s$, given that a positive measure of workers was promoted in period 2, current employers with history $(r, 0)$ do not find it profitable to retain the lowest-ability worker who was promoted since she has to be paid a wage that is higher than her productivity. Hence, there is a set of relatively lower-ability workers among the promoted workers who move to a new firm.

Proposition 2, part *a*: Now suppose that workers with $\theta \geq \hat{\theta}_2$ were assigned to job level 2 in period 2. These workers are more productive in a new firm in the current period since $\beta \geq s$. But since the original firm has an informational advantage about the ability levels of its own workers, it tries to retain the best of its promoted workers. Suppose the market believes that a promoted worker who comes to the firm for employment has expected ability θ^e; the outside wage for the promoted worker is $\max\{\theta^e(1 + \beta)rI^*, 1\}$. As long as $\hat{\theta}_2 \geq 1/(\beta + 1)rI^*$, the outside wage for a promoted worker is $\theta^e(1 + \beta)rI^*$. In the next part of the proposition we show that this true. At this outside wage, firm i retains a worker with ability θ if and only if $\theta(1 + s)rI^* \geq \theta^e(1 + \beta)rI^*$.

The cutoff level of ability above which a worker is retained is $\hat{\theta}_3 = \theta^e[(1 + \beta)/(1 + s)]$. Then, since a worker is retained if and only if $\theta \geq \hat{\theta}_3$, the conditional expected ability of the worker is $\theta^e = (\hat{\theta}_2 + \hat{\theta}_3)/2$. Solving for $\hat{\theta}_2$, we get

$$\hat{\theta}_3 = \hat{\theta}_2 \frac{\beta + 1}{1 + 2s - \beta} > \hat{\theta}_2.$$

Thus, workers with $\theta \in [\hat{\theta}_2, \hat{\theta}_3]$ move to a new firm. The wage for workers with $\theta \geq \hat{\theta}_2$ is

$$w_3^2(r, 0) = \frac{1 + s}{1 + 2s - \beta}(1 + \beta)\hat{\theta}_2 rI^*.$$

We show in part c of the proof that

$$\hat{\theta}_2 = \frac{1}{rI^*} \geq \frac{1}{(\beta + 1)rI^*}.$$

By substituting the value of $\hat{\theta}_2$, we get the wage as given in the proposition. Workers who were assigned to job level 1 in period 2, that is, those with $\theta < \hat{\theta}_2$, receive an outside wage according to their productivity in job level 1 in a new firm, which is 1.

Part b: The average wage of workers retained in the firm is

$$\frac{1}{rI} + \left[1 - \frac{\beta + 1}{(1 + 2s - \beta)rI}\right]\left[\frac{1 + s}{1 + 2s - \beta}(1 + \beta)\right].$$

The average wage of workers who turn over is

$$\left[\frac{\beta + 1}{(1 + 2s - \beta)rI} - \frac{1}{rI}\right]\left[\frac{1 + s}{1 + 2s - \beta}(1 + \beta)\right].$$

The average wage of workers in the turnover pool is greater than the average wage of retained workers if and only if

$$\frac{(3\beta + 1 - 2s) - (1 + 2s - \beta)rI}{(1 + 2s - \beta)^2}(1 + s)(1 + \beta) \geq 1.$$

The left-hand side of the above expression is increasing in β. At $\beta = s$, $(1 - rI)(1 + \beta) \leq 1$. At $\beta = 1$, $[(2 - s - srI)/s^2](1 + s) \geq 1$ for all $s \leq 1$ and $\frac{1}{2}rI^* \leq 1$. Hence workers who turn over earn a higher wage on average than retained workers if and only if β is high enough.

Part c: The probability that a worker moves to a new firm is $\hat{\theta}_3 - (1/rI^*)$. After substitution for $\hat{\theta}_3$, the expression that denotes this probability is

$$\Pr\left(\frac{1}{rI^*} \leq \theta \leq \hat{\theta}_3\right) = \frac{2(\beta - s)}{(1 + 2s - \beta)rI^*},$$

which is decreasing in I^*.

Part d: In period 2 a worker employed in a firm with $r_{i2} = r$ is always more productive in firm i than in a new firm. Hence all workers are retained in the same firm and there is no turnover. Given that $p \geq \frac{1}{2}$, for every $\beta < 1$, $\beta < [p(1+s) - (1-p)s]/p$. The wage for a promoted worker in the outside market isdetermined by her expected productivity in a job level 2 position in a new firm. So if the market believes that workers with $\theta \geq \hat{\theta}_2$ are promoted in firms with $r_{i2} = r$, then the wage for a promoted worker is $\hat{\theta}_2 rI^* + p\hat{\theta}_2 rI^*(1 + 2s - \beta)$, which is the total expected output of the least productive worker in a new firm. The reason is that in period 2, the expected output of all workers is higher in the current firm than in a new firm and the current employer can make wage counteroffers. Under these conditions, beliefs about worker ability in a new firm are driven by a winner's curse result. To see why, consider what happens if the new firm offers a wage that is higher than the expected output of $\hat{\theta}_2$. The current employer makes a counteroffer to retain a worker at this wage if and only if the expected output of the worker in the current firm is higher than this market wage. This in turn means that workers who move to a new firm had an expected output lower than this market wage, so that the new firm necessarily makes a loss on the workers who turn over at this wage. Thus the only belief about worker ability that is consistent in equilibrium is that it is $\hat{\theta}_2$.[16]

A worker who is not promoted is paid a wage of $1 + s$, which is the total expected output of a worker in job level 1 across periods 2 and 3. Comparing the profit from promoting a worker with that from keeping her in job level 1, we obtain the cutoff $\hat{\theta}_2 = 1/rI^*$. Substituting for $\hat{\theta}_2$ in the wage expression above, we get $1 + p(1 + 2s - \beta)$ as the job level 2 wage. QED

Proof of Proposition 3

First we derive the equilibrium investment in period 1. The expected profit from a worker in the following two periods for each possible R&D outcome vector is given as follows:

$$\pi^{00}(I) = s,$$

$$\pi^{0r}(I) = \int_0^{\hat{\theta}_2} s d\theta + \int_{\hat{\theta}_2}^1 [\theta(1+s)rI - 1] d\theta,$$

$$\pi^{r0}(I) = \int_0^{\hat{\theta}_2} s d\theta + \int_{\hat{\theta}_2}^1 [\theta(1+s)rI - w_2^2(r)] d\theta$$
$$+ \int_{\hat{\theta}_3}^1 [\theta(1+s)rI - w_3^2(r, 0)] d\theta,$$

$$\pi^{rr}(I) = \int_0^{\hat{\theta}_2} s d\theta + \int_{\hat{\theta}_2}^1 [3\theta(1+s)rI - w_2^2(r) - (\beta+1)] d\theta.$$

Then, the total expected profit from investing I in R&D in period 1 is

$$\pi(I) = (1-p)^2\pi^{00}(I) + p(1-p)[\pi^{0r}(I) + \pi^{r0}(I)]$$
$$+ p^2\pi^{rr}(I) - c(I).$$

[16] See Golan (2005) for a detailed explanation of this result.

The second derivative of the profit function is

$$\pi''(I) = p\left[(1+s)(2+p)\frac{1}{rI^3} + (1-p)(1+s)\frac{(\beta+1)^2}{(1+2s-\beta)^2 rI^3}\right] - c''(I).$$

A sufficient condition for the above to be negative and the profit function to be concave is that $3(1+s)(1/rI^3) < c''(I)$ for all $I \in [1/r, \bar{I}]$. We also need to ensure that the equilibrium investment level I^* is positive. If $I < 1/r$, even the highest-ability worker is more productive in job level 1, so it is not worthwhile to promote any worker in any period. In this case the profit in every contingency following the investment is $s - c(I)$, which is strictly decreasing in I and $I^* = 0$. In order to ensure that $I^* > 0$, we assume that there exists an investment level $\tilde{I} > 1/r$ such that $\pi(\tilde{I}) = s$. Then the equilibrium level of investment I^* solves $\pi'(I^*) = 0$.

Next we derive the optimal investment, which is obtained by maximizing the total expected surplus from efficient assignment and turnover following the investment. This represents the first-best outcome in the market. The output from investing I for each R&D outcome vector is

$$\begin{aligned} Y^{00}(I) = Y^{0r}(I) &= \int_0^{\hat{\theta}_2^o(0)} 2(1+s)\,d\theta + \int_{\hat{\theta}_2^o(0)}^1 \theta rI[1 + 2p(1+s) \\ &\quad + (1-p)(1+\beta)]\,d\theta, \\ Y^{r0}(I) &= \int_0^{\hat{\theta}_2^o(r)} 2(1+s)\,d\theta + \int_{\hat{\theta}_2^o(r)}^1 \theta rI(2+s+\beta)\,d\theta, \\ Y^{rr}(I) &= \int_0^{\hat{\theta}_2^o(r)} 2(1+s)\,d\theta + \int_{\hat{\theta}_2^o(r)}^1 3\theta rI(1+s)\,d\theta, \end{aligned}$$

where

$$\hat{\theta}_2^o(0) = \frac{2(1+s)}{[1 + 2p(1+s) + (1-p)(1+\beta)]rI}$$

and

$$\hat{\theta}_2^o(r) = \frac{2(1+s)}{[(1+s)(1+2p) + (1-p)(1+\beta)]rI}.$$

These are the efficient period 2 promotion cutoffs for each realization of r_{i2}. Note that since wages are transfers between firms and workers and there are no other production costs in the model, output is equal to surplus in periods 2 and 3. So we obtain the efficient period 2 promotion cutoffs by comparing the total output from assigning a worker to job level 1 in the same firm to the total output from assigning her to job level 2 in the same firm if $r_{i2} = r$ or job level 2 in a new firm with a successful period 2 outcome if $r_{i2} = 0$. If $r_{i2} = 0$, then workers with $\theta \geq \hat{\theta}_2^o(0)$ should move to a firm with successful R&D in period 2, while the remaining workers should stay in the same firm. If the firm has a successful draw in period 3, all workers should be retained, and workers should be assigned to job level 2 if and only if $\theta \geq \hat{\theta}_2^o(r)$. The total expected surplus from investing I is

$$Y(I) = (1-p)^2 Y^{00}(I) + p(1-p)[Y^{0r}(I) + Y^{r0}(I)] + p^2 Y^{rr}(I) - c(I).$$

The second derivative of the expected surplus function is

$$\frac{d^2 Y(I)}{dI^2} = (1-p)\frac{d^2 Y^{00}(I)}{dI^2} - \frac{4p(1+s)^2}{[(1+s)(1+2p)+(1-p)(1+\beta)]^2 rI^3} \times [(1-p)(2+s+\beta) - 3p(1+s)] - c''(I).$$

For r high enough the above is negative, so the function is concave.

Let I^o denote the optimal investment. Then I^o solves $Y'(I^o) = 0$ We assume that the I^o lies in the range in which $\hat{\theta}_2^o(r) < \hat{\theta}_2^o(0) < 1$ so that a positive measure of workers are assigned to job level 2 in period 2 at the efficient outcome. Some extensive algebra shows that $Y'(I^*) > 0$. This implies that $I^o > I^*$. Also $\partial Y'(I)/\partial\beta > 0$ so that $\partial I^o/\partial\beta > 0$ while $\partial\pi'(I)/\partial\beta < 0$ so that $\partial I^*/\partial\beta < 0$. This means that as β increases, the equilibrium level of investment diverges more and more from the optimal level; that is, as β increases, $I^o - I^*$ increases.

Next we show that the equilibrium job assignment is inefficient. First note that for any given level of investment, a positive measure of workers ought to be assigned to job level 2 in a new firm in period 2 when $r_{i2} = 0$. However, in equilibrium all workers are retained in job level 1 in the same firm. If $r_{i2} = r$, $\hat{\theta}_2(r) < 1/rI = \hat{\theta}_2$; hence fewer workers are assigned to job level 2 than is efficient for maximizing output at any given level of investment. Further, since $I^* > I^o$ and $(\partial/\partial I)\hat{\theta}_2^o(r) < 0$,

$$\hat{\theta}_2^o(r, I^o) < \hat{\theta}_2^o(r, I^*) < \frac{1}{rI^*}.$$

In order to see how β affects the promotion inefficiency, note that since $\partial I^*/\partial\beta < 0$, $(\partial/\partial\beta)(1/rI^*) > 0$. On the other hand, $\partial\hat{\theta}_2^o(r)/\partial\beta < 0$ because of both the direct effect of β on $\hat{\theta}_2^o$ at any given level of investment and the positive effect on optimal investment. Thus as β increases, the difference between the equilibrium and optimal promotion cutoffs for firms with $r_{i2} = r$ increases. For firms with $r_{i2} = 0$, $\partial\hat{\theta}_2^o(0)/\partial\beta < 0$, so again the promotion inefficiency increases with β. QED

Proof of Proposition 4

The average ability of a worker who changes firms in period 3 from an $(r, 0)$ firm is

$$\frac{\hat{\theta}_2 + \hat{\theta}_3}{2} = \frac{(1+s)\hat{\theta}_2}{1+2s-\beta}.$$

Since $\partial\hat{\theta}_2/\partial\beta > 0$, it follows that

$$\frac{\partial}{\partial\beta}\left(\frac{\hat{\theta}_2 + \hat{\theta}_3}{2}\right) > 0.$$

QED

Proof of Proposition 5

Ability level $\hat{\theta}_3$ is increasing in β, and at $\beta = 1$, there is complete turnover of all promoted workers if $\hat{\theta}_3 \geq 1$. This is true for $I^* \leq \hat{I}$, where $\hat{I} = 1/sr$.

We can show that $\pi'(\hat{I})$ is increasing in p:

$$\pi'(\hat{I})_{p=1/2} = \frac{5}{8} r(1+s)^2(1-s) - c'(\hat{I}),$$
$$\pi'(\hat{I})_{p=1} = \frac{3}{2} r(1+s)^2(1-s) - c'(\hat{I}).$$

Let us define

$$\psi_1 = \frac{5}{8} r(1+s)^2(1-s)$$

and

$$\psi_2 = \frac{3}{2} r(1+s)^2(1-s),$$

where $\psi_1 < \psi_2$. Then if $c'(\hat{I}) > \psi_2$, then for all $p \in [\frac{1}{2}, 1]$, $\pi'(\hat{I}) < 0$ so that $I^* < \hat{I}$ and $\hat{\theta}_3 \geq 1$ for β high enough. If $\psi_1 \leq c'(\hat{I}) \leq \psi_2$, then define $\hat{p}$ as the p that solves $\pi'(\hat{I};\ \hat{p}) = 0$. In this case, $\pi'(\hat{I}) \leq 0$ if and only if $p \leq \hat{p}$. Thus for $\frac{1}{2} \leq p \leq \hat{p}$, we again have that $I^* \leq \hat{I}$, so that $\hat{\theta}_3 \geq 1$ for β high enough and all promoted workers turn over when $(r, 0)$ occurs. QED

Proof of Proposition 6

Let us define $\beta_k = \beta - \delta_k$.

Part *a*: From proposition 5, let us consider the case in which all promoted workers move to a new firm if their current employer has an $(r, 0)$ outcome. First we show that the equilibrium investment in period 1 does not depend on β_k. Here the equilibrium investment solves $\pi'(I^*) = 0$, or

$$p^2 \int_{\hat{\theta}_2}^{1} 3\theta(1+s) r d\theta + 2p(1-p) \int_{\hat{\theta}_2}^{1} \theta(1+s) r d\theta - c'(I^*) = 0.$$

Note that I^* is independent of β_k. Hence job assignments and $\hat{\theta}_2$ are also independent of β_k.

Now let us look at the effect of β_k on postinvestment industry output from I^*:

$$\frac{dY_k(I^*)}{d\beta_k} = p(1-p)\left(\int_{\hat{\theta}_2}^{1} \theta r I^* d\theta\right) > 0.$$

Since the direct effect of β_k on output is positive and the indirect effect through investment and job assignment is absent, output is higher if β_k is lower. QED

Part *b*: Now let us see what happens when some promoted workers are retained in the current firm. Then I^* solves $\pi'(I^*) = 0$, or

$$p^2 \int_{\hat{\theta}_2}^{1} 3\theta(1+s)rd\theta + p(1-p)\left[2\int_{\hat{\theta}_2}^{1} \theta(1+s)rd\theta - \frac{d\hat{\theta}_3}{dI}\int_{\hat{\theta}_3}^{1}(1+s)rI^* d\theta\right] - c'(I^*) = 0.$$

In this case, β_k affects the profits that the firm makes on its retained job level 2 workers, and hence it affects the equilibrium investment. It can be checked that $(d/d\beta_K)\pi'(I) < 0$. Hence $dI^*/d\beta_k < 0$. Moreover, promotion efficiency also worsens, and hence industry output further decreases. At the same time, the direct effect of β_k on output is still positive. Hence, the overall effect is ambiguous. QED

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