Innovation, Knowledge Flow, and Worker Mobility

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Abstract

In knowledge-driven industrial markets employee turnover is often quite high despite each firm’s interest in restricting knowledge flow resulting from employee departures. We present a dynamic contracting and matching model of the employment relationship between a firm and a worker (engineer) that provides an equilibrium explanation for high turnover. Incompleteness of the contracting relationship makes it optimal for firms to adopt open R&D environments as a recruitment inducement when labor is in relatively short supply. Such environments facilitate turnover. We examine how openness of R&D environments varies according to labor market conditions, expected quality of initial firm-employee match, legal protection of IP, and the longevity of the product cycle. These results are useful for understanding why geographic clusters often foster innovation.

1. Introduction

Starting with Marshall (1920) and Jacobs (1969), economists, sociologists and geographers have come to recognize that geographic clustering and strategic location of economic activity raise the rate of growth and innovation. One explanation for this is that innovation is facilitated by knowledge spillovers and exchanges of information that occur when there is geographic concentration. This hypothesis is supported by recent empirical work showing a link between innovative activity and geographic concentration.1

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1See Jaffe, Trajtenberg, and Henderson (1993), Ciccone and Hall (1992), Henderson, Kuncoro, and Turner (1995), Glaeser et. al. (1992), and Ellison and
Yet the mechanisms for knowledge spillovers and the incentives producers have for exchanging information are not well understood.\footnote{There is little theoretical or empirical work attempting to explain how knowledge spillovers actually occur. One exception is Acemoglu (1996) who demonstrates that imperfect matching of skilled workers to firms can produce spillovers in human capital accumulation. Gersbach and Schmutzler (2003) investigate technological spillovers resulting from migration of workers between rival firms. Their analysis does not address the effect of geographic concentration on the likelihood of spillovers however. Helsley and Strange (2002) argue show that geographic concentration may induce greater innovation through increased availability of input supplies and not through technological spillovers per se.} For instance, Saxenian (1994) argues that the frequent social and professional meetings of Silicon Valley engineers and the ease with which workers changed jobs led to the rapid dissemination and cross fertilization of ideas which fueled innovation in the Silicon Valley. But what incentives do profit maximizing firms have for permitting private information to be shared with employees from other companies? What benefit does a firm derive by permitting its employees to move to another company? After all, intellectual capital is the lifeblood of high-technology firms and much of that capital is embodied in a firm’s “star” workers. Why do employees move frequently without resistance from their employers in some knowledge-driven market environments? Our purpose here is to address these puzzles.

This paper provides a theoretical explanation for why knowledge based markets exhibit different amounts of interfirm information flow and different degrees of labor mobility.\footnote{Labor turnover can be quite high. Saxenian (1994) reports Silicon Valley turnover rates reached above 30 percent and over 50 percent for small firms during some years.} Two elements of the employer-employee relationship are particularly important for our explanation. First, R&D is inherently unpredictable and hard to measure. Unpredictability means that the research sponsored by one firm may sometimes have a higher valued use with another company. Further, the difficulty of measurement means that contracts for the delivery

\footnote{Glaeser (1997). Hanson (2001) provides a current summary and critique of this empirical evidence.}
and transfer of R&D will be incomplete. Second, labor mobility is protected by law and an R&D firm’s intellectual property (IP) is partially bound up in its workers. The embodiment of IP in employees means that departing workers will frequently take valuable IP to their new employer, in some cases effectively denying the original employer return to its IP investment.

These features of the economic environment preclude a contracting resolution to the conflict between employees who seek job mobility and firms wishing to protect their investment in R&D. Firms moderate undesired worker separations by decreasing the “openness” of the research arrangement through restrictions on an employee’s access to outside information and enforcement of legal sanctions for unauthorized use of IP. The openness of the research arrangement that the firm commits to determines its ability to attract qualified researchers and this, in turn, is determined by the parties’ relative ex ante bargaining power.

In practice, we observe wide variation in the openness of research environments. At one end are closed companies like Procter & Gamble that discouraged technical people from joining industry trade associations and imposed stringent rules over employee conversations held outside the firm (Swasy 1993). At the other end are firms like Tandem Corporation and Syntex which have allowed outsiders and even competitors access to its facilities and staff. In this paper we indicate

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4 Hoch et. al. (2000, p. 88) in a study of software firms remark that “the core knowledge of new products often resides with the core employees” and recount one businessman’s view that the assets of his firm go down the elevator every evening. See also Bhide (1994) and Klepper and Sleeper (2005) who find evidence that links ideas used in new start-ups to previous jobs.

5 In a related paper Motta and Roende (2002) examine the effects of a covenant-not-to-compete clause on labor mobility and labor contracts in a market where employees can leave to generate duopoly competition for the incumbent. See also Franco and Mitchell (2005).

6 Tanzer (1993) argues that Tandem’s openness was instrumental in allowing it to attract top computer industry talent. Kornberg (1995, p. 232) states that “to attract and retain creative and productive scientists, industrial management must provide an open atmosphere that encourages free discussion...both from within
how variations in the openness of research environments are shaped by the degree of spatial agglomeration in the market, by firm and employment placement efficiency, by the technology of production, and by the legal protection of IP rights.

Section 2 of this paper presents a dynamic contracting and matching model of employment between a firm and a worker (engineer) that captures the features of the economic and institutional environment discussed above. A firm and an engineer meet to produce a new product. During innovation, the engineer may learn whether his research is best commercialized by his current employer or another company. The employment contract is necessarily incomplete. Consequently, the openness of the innovation process is governed by the firm’s policy regulating the information exchange between employees inside and outside the firm and the mobility afforded the engineer in moving to another company. In equilibrium, market forces determine the openness of these arrangements as firms compete to hire engineers from a limited applicant pool.

Section 3 applies our model to examine how contract openness, with corresponding impacts on worker mobility, varies according to the market environment. We find that an engineer’s power to bargain for openness provisions depends on his outside options and ability to find employment with another firm. Outside options are determined by the industry environment as characterized by the efficiency of the labor market for placing firms with workers, the predictability of research activity, the legal protection of IP, and the longevity of the product cycle. We find that:

- Efficient placement markets promote open arrangements. With efficient placement, the scarcity value of engineers increases, permitting them to bargain for more open agreements.

- Predictable research induces more open arrangements. The
quality of firm-engineer matches improves with the predictability of research. Firms offer more open arrangements when the likelihood of worker separations declines as a result of better initial matches.

- **Contracts are more open when the firm holds strong IP rights.** Engineers bargain for more open arrangements to compensate for payment reductions resulting from stronger employer IP rights.

- **Contracts are more open with shorter product life cycles.** The scarcity value of engineers increases with shorter life cycles permitting them to bargain for more open arrangements.

Various factors affecting knowledge movement through employee departures have been studied by Anton and Yao (1995), Anand, Galetovic, and Stein (2004), Hellmann (2005), Kim and Marschke (2005), and Klepper and Thompson (2005). Our paper differs from those by allowing a firm to take an action (e.g. establish an openness policy) prior to the realization of innovation outcomes that encourages some level of departure. The setting we study is closest to that of Kim and Marschke which also identifies how employee departure to a higher-valued use makes it easier to attract an employee initially (with a lower wage). In addition to allowing a pre-innovation action, our model differs from their model by embedding firm-engineer interactions in an equilibrium labor market.\(^7\) These differences allow us to explore a range of other issues including the relationship between openness and intellectual property protection, various aspects of engineer shortages, and the effect of geographic clusters.

\(^7\)Kim and Marschke’s model does allow the firm to affect the likelihood that an engineer will depart by permitting the firm to patent (or not) after the innovation realization. But their use of the patent decision for this purpose is somewhat awkward as the firm’s decision to patent is likely to depend more on excluding other firms from imitating than on reducing an engineer’s incentive to depart.
2. The Model

This section models the interaction between firms and engineers. Engineers and firms are initially matched in a placement market as described in section 2.1. Sections 2.2 - 2.3 describe how the parties learn about the quality of their match, determine where to commercialize their innovations, and finally how their payoffs from the process are determined. Figure 1 provides a timeline for the model.

We describe the initial bargaining between engineers and firms to determine the openness of the research process in section 2.4. Section 2.5 characterizes the preferences of the parties for openness in innovation.8

A maintained assumption throughout the model is that contracts cannot be written over future intellectual property development outcomes. This assumption captures the difficulties associated with pre-

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8Our focus is on how a firm chooses its research environment as part of its effort to attract workers. Thus, we do not address standard labor economics concerns such as allocation of risk, protection of specific investments, or motivation of employees. See, e.g. Malcomson (1999) for a survey of work on these topics. This emphasis on the endogeneous determination of the employee’s awareness of an outside match in the context of contract incompleteness also distinguishes our work from Jovanovic (1984).
dicting and verifying innovation. Therefore, the initial contract cannot be contingent on the results of the development process. Payments for innovation are determined once the commercialization outcome is observed and this ex post negotiation is anticipated in the initial bargaining.

2.1. Matching of Firms and Engineers

The market consists of a population of firms, $F$, and engineers, $E$. Each firm hires a single engineer to create a specific product for the firm to commercialize and market. The engineer performs the research while the firm provides capital and marketing know-how to commercialize the product.

There is a continuum of firms and engineers. The firm population size is normalized to be of measure one. The size of the engineer population is $P_E$. In what follows we examine the effects of varying labor supply $P_E$ on research agreements. Firms and engineers form matches. The equilibrium levels of unemployed engineers and inactive firms, denoted respectively by $\rho_E P_E$ and $\rho_F$, are determined by two conditions. First, in each period, the number of employed engineers and active firms are equal. Each active firm hires one engineer, implying,

\[(1 - \rho_F) = (1 - \rho_E)P_E.\]  

Second, inactive firms and unemployed workers seek new matches. A match is created when a vacant firm finds an unemployed worker. Each period the likelihood a vacant firm finds an unemployed engineer follows a Poisson process with success rate $\alpha \rho_E P_E$. The

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9Our results are essentially unchanged if the possibility that firms hire multiple employees is allowed.
10 We assume only firms search for engineers and that firm search costs are zero.
11 We assume $\alpha \rho_E P_E < 1$ so that vacant firms fail to find a match with some probability.
search efficiency parameter $\alpha$ measures a vacant firm’s ability to identify prospective engineers. The likelihood of a successful match increases proportionately with the number of available engineers, $\rho_E P_E$. We assume the individual probability of successful matching is independent of the number of searching firms so the aggregate number of new matches each period is $\alpha(\rho_F)(\rho_E P_E)$. The lifetime of an existing job follows a Poisson process with a death rate of $\delta \in (0, 1)$. Deaths occur as existing products become obsolete. In equilibrium, jobs are created and destroyed at the same rate, requiring,

$$\alpha(\rho_F)(\rho_E P_E ) = (1 - \rho_F)\delta. \quad (2)$$

2.2. Suitability of Research

This section develops a reduced form model describing how research and development is directed and applied by $E$ and $F$. (Henceforth, we will use “research” to include development.) After an engineer and a firm meet, the engineer begins research. Research results are unpredictable and they depend on the quality of the $E - F$ match. After completing research $E$ and $F$ learn the innovation’s commercial value. The value of commercialized research for application inside the firm is $\pi_I$. With probability $\lambda \in (0, 1)$, $\pi_I$ is high (equal to $\pi_H$) and with probability $1 - \lambda$ it is low (equal to $\pi_L$), where $\pi_H > \pi_L$. $\lambda$ is the ex ante probability of a good match.\(^{12}\)

Conditional on the match being poor, there is a probability $\mu \in (0, 1)$, that $E$ learns the identities of the outside firms where his research could be applied more profitably. In this case, which occurs with probability $(1 - \lambda)\mu$, the outside value of commercialization, $\pi_O$, is high (equal to $\pi_H$). In all other instances the value of outside commercialization is assumed to be worthless, so that $\pi_O = 0.\(^{13}\)

\(^{12}\)For example, a software engineer performs research to develop animation for a video game manufacturer. After research is complete the parties may discover the software has greater value for another application such as in virtual reality programs used by industrial engineering firms.

\(^{13}\)Either the initial match is good in which case the outside commercialization
2.3. **Commercialization Decision and Payoffs**

Once the research is completed and $\pi^I$ and $\pi^O$ are known, $E$ and $F$ decide where to commercialize and how to split the resulting surplus. The parties will commercialize together, except possibly when the outside commercialization value is high, which we discuss below. If $E$ and $F$ remain together for commercialization, they generate a present value flow of joint surplus, $S(\pi^I)$, recursively defined by,

$$S(\pi^I) = \pi^I + B[(1 - \delta)S(\pi^I) + \delta(V_E + V_F)]$$

(3)

where $B \in (0, 1)$ is the discount factor. The expected value of inside commercialization is the current period surplus, $\pi^I$, plus the discounted expected surplus in the following period, if the product survives (with probability $1 - \delta$), plus the expected surplus, $V_E + V_F$, if the product dies and the parties become unemployed. $V_i$ is the expected unemployment value for $i = E, F$.

$E$ and $F$ are unable to contract for the division of this surplus since a third party (the court) cannot determine its value. We assume the parties split the additional surplus in excess of their outside options by Nash bargaining. If the parties separate, $F$ retains possession of the IP. $E$ becomes unemployed yielding him expected surplus of $V_E$. $F$ returns to the unemployment pool yielding her expected surplus of $V_F$. In addition, $F$ receives some portion of the expected surplus, $\varepsilon \pi_I$, from commercializing the innovation without $E$'s assistance. The portion of value, $\varepsilon \geq 0$, that $F$ captures increases with the degree to which the IP was codified before $E$ left and on her legal rights to use the IP. The parties’ respective shares of the surplus denoted by value is low, or $E$ cannot direct his research to attain its outside highest value because he does not know its best outside application. For convenience we assume the outside commercialization value is zero in those cases. Note, however, that even “poor” matches are valued by $F$.

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14 We assume that $E$'s next employer will be extremely unlikely to be able to use the IP.
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\[ Y_j^I(\pi^I) \text{ for } j = E, F \text{ are,} \]

\[ Y_E^I(\pi^I) = \frac{S(\pi^I) + V_E - (V_F + \varepsilon\pi^I)}{2}, \]

\[ Y_F^I(\pi^I) = \frac{S(\pi^I) + (V_F + \varepsilon\pi^I) - V_E}{2} \]

The employee may receive his share of the surplus as a wage payment and/or as an ownership share in the company.

The innovation is commercialized outside the firm when \( \pi^O = \pi_H \) and \( F \) is unsuccessful in using the law to prevent \( E \) from departing with the IP. We assume that \( E \) is financially constrained and therefore unable to compensate \( F \) for the lost IP value when \( E \) moves. Consequently, \( F \) prevents \( E \) from leaving with the innovation when possible. We also assume non-compete clauses and intellectual property rights protect \( F \) by preventing \( E \) from leaving with probability \( \gamma \in (0, 1) \).

When \( E \) can not be kept from leaving, the parties’ respective shares of the surplus denoted by \( Y_j^O(\pi_H) \) for \( j = E, F \) are

\[ Y_E^O(\pi_H) = S(\pi_H) - V_F, \quad Y_F^O(\pi_H) = V_F \]

(5)

Here we have assumed that \( E \) gets all the surplus from its match with an outside firm. One might also think of this as giving \( E \) bargaining power based on a reservation utility that involves going to another (already identified) high match firm.\(^{15}\)

Each party’s expected surplus from a match denoted by \( W_j \) for \( j = E, F \) is,

\[ W_j = \sigma_H^I Y_j^I(\pi_H) + \sigma_L^I Y_j^I(\pi_L) + \sigma^O Y_j^O(\pi_H) \]

(6)

where \( \sigma_H^I = \lambda, \sigma_L^I = (1 - \lambda)(1 - \mu(1 - \gamma)) \), and \( \sigma^O = (1 - \lambda)\mu(1 - \gamma) \) are the probabilities that commercialization takes place inside the firm when \( \pi^I = \pi_H, \pi^I = \pi_L \), and outside the firm, respectively. The expected surplus for each party is the probability weighted sum of surpluses arising when the innovation is commercialized inside and outside the firm.

\(^{15}\)This assumption simplifies the algebra. Our qualitative results would continue to hold if we modified the model to have the surplus divided by Nash bargaining with a single outside firm.
2.4. Negotiation of Arrangements

When $E$ and $F$ initially meet they negotiate an employment agreement which coupled with the underlying legal environment governs their subsequent interaction. Since research is unpredictable and difficult to specify, the contract is necessarily incomplete. For instance, we assume that contracts specifying payment to $F$ in case $E$ should leave to develop his research at another firm are infeasible and unenforceable.\(^{16}\) However, the parties can commit to a set of contractible terms $\{P, \mu; \gamma\}$ that determine the ground rules for the employment relationship.

- **Direct Payment**: $P$ is a non negative payment from $F$ to $E$. $E$ is cash constrained and unable to make positive payments to the firm. When $P$ is positive it can take the form of a cash transfer or a wage paid to $E$, or (with an inessential modification to the model) a stock option which guarantees $E$ a share of future firm profits if $E$ remains with the firm.\(^{17}\)

- **Information Control Policy**: $\mu$ is the likelihood $E$ learns about a superior outside application for his research. We assume $F$ commits to a particular $\mu$ through an information control policy regulating how $E$ acquires, shares, and disseminates informa-

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\(^{16}\)Our model greatly simplifies the actual problems associated with contracting over R&D. Such complexities include the inability of third parties to observe a transfer of intellectual property from one firm to another and to know what property was developed at the different firms. Given these complexities, we feel comfortable with our assumption that the parties cannot contract over future R&D outcomes.

\(^{17}\)In theory the firm could condition the payment of $P$ on the employee’s commercialization of the innovation. While this arrangement might deter $E$ from leaving for outside commercialization, there is no strict advantage to $F$ from doing so. In Observation 2 below we show that whenever $P > 0$, so that $F$ pays $E$ initially, the first-best contract involves a cash transfer. Stock options which distort $E$'s mobility are not optimal because they reduce the total surplus generated under the contract.
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This policy is implemented through rules regarding the exchange of knowledge with outsiders, publication of research findings, and participation in industry workshops or standard-setting organizations, and professional seminars. This policy is designed to acquire valuable information from outsiders. See von Hippel (1988) who reports that voluntary sharing of proprietary knowledge is common in some industries. We abstract from this purpose.

Information control policy is an important element of a firm’s organizational culture which many studies suggest is an important consideration for job applicants (e.g., Hoch et al. 2000). Liebeskind (1997) discusses a number of rules and sanctions firms use to control information outflow. Sometimes these rules include restrictions on locations where employees can visit or even socialize. Howells (1994) reports that allowing employees to publish makes it easier to recruit technical people. Internal organizational structure also impacts the diffusion of knowledge.

Because commercialization has not yet occurred, the inability to contract over future innovation assumption eliminates the possibility that the outside firm can bargain with F for E’s services when no-compete contracts or trade secret law prevent E’s departure. F might, however, allow E to depart if it could enforce ex post claims on the unauthorized use of its intellectual property (IP), but such ex post claims are likely to be difficult to enforce. Note that even if it were possible for an F with control rights over the IP to impose a claim on the outside firm after commercialization, E may be forced to stay (or may choose to stay) with F. F would not allow E to go to an outside firm if F can not capture as much from the anticipated three-way split of the high match profits than F could capture with a two-way split of the low match profits. Similarly, if F were willing, it might be that E would not be willing to leave knowing that F would make subsequent claims.
and the nature of technology.21

E and F negotiate their agreement, \( \{ P, \mu; \gamma \} \), employing the Nash bargaining solution. If they fail to reach agreement \( E \) and \( F \) return to the unemployment pool and receive \( V_E \) and \( V_F \), respectively. The equilibrium unemployment surpluses for \( E \) and \( F \) are defined recursively by

\[
V_E = \alpha \rho_F (BW_E + P) + B (1 - \alpha \rho_F) V_E \\
V_F = \alpha \rho_E P_E (BW_F - P) + B (1 - \alpha \rho_E P_E) V_F.
\]

The expected surplus from being unemployed is the probability of securing a match multiplied by the expected surplus from a match, plus the probability of remaining unemployed next period multiplied by the discounted surplus from being unemployed.

Given the equilibrium values \( V_E \) and \( V_F \), the firm selects the contract terms \( P \) and \( \mu \) to maximize her net surplus, \( BW_F - P \), subject to the constraint that \( E \) must receive at least as much net surplus as \( F \). Further, since \( E \) is liquidity constrained, only positive payments from \( F \) to \( E \) can be used.

\[
\max_{\{ P, \mu \}} BW_F - P \\
\text{subject to} \quad BW_E + P - V_E \\
\quad \geq BW_F - PY_F - V_F \\
\quad P \geq 0 \\
\quad \mu \in [\mu_L, \mu_H]
\]

21Although no-compete clauses are rather ubiquitous in the U.S., such clauses often lack force (see, e.g. Sterk 1993). Trade secret law is more favorable to employers and can, in principle, significantly impede R&D employee movement. Merges (2000), however, notes that such suits become quite difficult for an employer to win when the employee departs while the idea is effectively still in his or her head, giving employees a “de facto exit option.”
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To avoid unnecessary complications we assume $F$ determines the probability $\mu$ through the costless implementation of an information control policy. The upper and lower bounds $\mu_H$ and $\mu_L$ depend on the industry environment in which research occurs. These bounds are determined by the extent of social networks and institutions for making job information available, as well as the density of firms in the region, proximity to research universities, and the presence of strong professional networks.\(^{22}\)

2.5. Preferences for Contract Openness and First Best Contracts

In an open research arrangement the firm permits its employees to share research with colleagues outside the firm. It also gives its employees more freedom to develop their ideas and innovations for internal as well as external applications. An important implication of our analysis is that firms and engineers have opposing preferences for contract openness.

**Observation 1:** $E$ prefers an open research arrangement, $\partial W_E / \partial \mu > 0$ and $\partial W_E / \partial \gamma < 0$ whereas $F$ prefers a closed arrangement with $\partial W_F / \partial \mu < 0$ and $\partial W_F / \partial \gamma > 0$.

$E$ prefers an open information-exchange policy because it permits him to better direct his innovative activity to the most valuable application. In contrast, $F$ prefers a closed policy, as it allows her to better control $E$'s research. $E$ and $F$ also have conflicting preferences regarding the strength of legal protection of IP. The extent of legal protection is particularly important because research contracts are incomplete.\(^{23}\) Preventing $E$ from moving with IP protects $F$'s research investment. There are other benefits for $F$ of IP protection, which are not modelled but are nonetheless important. Protection of IP

\(^{22}\)See, e.g., Porter (1990) and Saxenian (1994) for discussion of networks and institutions in geographic clusters.

\(^{23}\)This is an important message in Grossman and Hart (1986) and Aghion and Tirole (1994). See also Anton and Yao (1995) for a contract failure explanation for employee start-ups.
discourages $E$ from pursuing outside research opportunities as leverage in subsequent negotiations. Also, controlling $IP$ permits the firm to retain its engineers more easily without distorting job assignments and delaying promotions to key employees.\textsuperscript{24}

While the opposing preferences between $E$ and $F$ for an open arrangement are clear, which type of contract, open or closed is most efficient?

Observation 2: The efficient, first-best, contract is open. The contract permits maximum information flow with $\mu^* = \mu_H$, and, minimal protection of IP with $\gamma^* = 0$. The contract is implemented by a transfer payment \[ P^* = \frac{1}{2}(BW_F(\mu^*, \gamma^*) - V_F) - (BW_E(\mu^*, \gamma^*) - V_E) \]

The open arrangement provisions in the contract ensure that the total surplus from innovation is maximized. The initial payment, $P^*$, enables the parties to divide the additional surplus created by the arrangement as required by the Nash bargaining solution.\textsuperscript{25}

### 2.6. Efficient Open-Constrained Equilibria

In practice, the parties will be unable to attain the first-best arrangement whenever $E$ is required to initially post a payment with $F$. Imperfect capital markets and the inability of creditors to monitor innovative activity will prevent $E$ from financing the required payment.\textsuperscript{26} As a result, research arrangements between $E$ and $F$ will be second-best, open-constrained agreements. In open-constrained agreements the firm restricts information flows and inhibits worker mobility to earn its share of rents.

\textsuperscript{24}Gibbons and Waldman (1999) provide an interesting summary of strategies firms employ to reduce employee mobility.

\textsuperscript{25}This finding is consistent with Pakes and Nitzan (1983) and Kim and Marschke (2005).

\textsuperscript{26}Cash constraints will also prevent $E$ and $F$ from implementing expost renegotiation procedures for overcoming incomplete contracts, as proposed by Edlin and Reichelstein (1996).
More formally, we define an open-constrained agreement and market equilibria as follows. Let \( m = \{P_E, \alpha, \lambda, \varepsilon, \gamma, \delta\} \) describe the market environment.

**Definition 1** Given \( m \), an open-constrained agreement consists of a probability of learning about an outside best application, \( \mu(m) \in [\mu_L, \mu_H] \) which solves (FP) subject to \( P = 0 \).

In an open-constrained agreement, \( \mu(m) \) is the critical learning probability that provides for an equal ex ante division of the expected surplus between \( F \) and \( E \) when cash constraints preclude the use of transfer payments.

**Definition 2** Given \( m \), an open-constrained equilibria consists of a seven-tuple of values \( \{\mu(m), V_E(m), V_F(m), W_E(m), W_F(m), \rho_E(m), \rho_F(m)\} \) satisfying conditions for efficient open-constrained agreements, the unemployment value equations (7) and (8), the match surplus equations (6), and the steady state employment and job creation conditions, (1) and (2).

By examining how the properties of the open-constrained agreement vary with changes in the environment \( m \), we can understand what factors determine the degree of contract openness in equilibrium. Table 1 summarizes the comparative static predictions of our model. The details of the comparative statics derivation and a demonstration of existence and uniqueness of open constrained equilibria are provided in the Appendix.

### 3. What Determines Contract Openness?

Why are research relationships relatively open in some settings, like the Silicon Valley, but not so in others? What variations in the operating environment cause relations between firms and employees to differ? To address these questions we examine how variations in placement market conditions, quality of information exchange, legal institutions, and technology affect research arrangements.
3.1. The Labor Market

The labor market is characterized by the supply of engineers, $P_E$, relative to firms. In equilibrium, a scarcity of qualified engineers, as often observed in young industries like the software industry, will likely enhance $E$’s relative bargaining power (reflected by the difference in $E$’s and $F$’s outside options, $V^E - V^F$). As $E$’s bargaining power increases, $F$ offers greater concessions to attract and retain $E$. These concessions result in more open arrangements: $F$ gives $E$ a greater chance to communicate with his colleagues outside the firm. These opportunities increase the likelihood that $E$ learns about a superior outside application. In equilibrium, worker mobility increases as $E$ separates from $F$ more frequently to pursue better opportunities.

These conjectures are supported by the comparative static predictions of our model (see row 1 of Table 1).

Observation 3: $E$ commands greater bargaining power when researchers are in relative short supply. As $P_E$ decreases and $E$ gains bargaining power, the research arrangement becomes more open; inter-firm information flow is encouraged and worker mobility increases. As the supply of engineers decreases, total surplus and engineer surplus increase, while firm surplus decreases.

A striking prediction of Observation 3 is that total surplus as well as the sum of all engineers’ surpluses, increase with a reduction in the supply of engineers. As the supply of engineers decreases, engineers command more open agreements.\textsuperscript{27} These agreements are more efficient, allowing for more movement of engineers to higher-valued employment. The increased efficiency of the research process more than compensates for the reduction in the supply of researchers. The result also implies that bargaining power will not only affect the distribution of gains among $E$ and $F$, but also partly determines the

\textsuperscript{27}Closed relationships are predicted when the labor market favors the firm. For example, Procter & Gamble, which has long dominated many of its businesses, has historically maintained a closed environment and has a reputation for suing ex-employees (Swasy 1993).
efficiency of the research process itself.\textsuperscript{28}

The salutary effects of a relative engineer shortage is capped by $\mu_H$. Thus, in really tight labor markets firms in geographic clusters with their inherently higher $\mu_H$ will have advantages stemming from more efficient employment arrangements relative to geographically isolated firms. This advantage may be a factor in a firm’s decision to locate in a cluster.

Observation 3 indicates how an employee’s bargaining power can substitute for his lack of liquidity in obtaining a more open research arrangement. If an engineer were not cash constrained, he would optimally pay the firm an initial fee in return for receiving an open contract. The open contract would afford the engineer greater freedom in developing and commercializing his intellectual property. When $E$ is cash constrained he can nonetheless command an open agreement provided he has sufficient bargaining power.\textsuperscript{29} This prediction is consistent with David’s (1998) finding that scientists have been able to establish “open science institutions” as a result of their ability to command greater rents.

Aside from the relative supply of engineers, the labor market is also characterized by $\alpha$, the search efficiency of the matching market. The clustering of similar firms and engineers in a geographic area facilitates the meeting of unengaged firms and engineers by reducing the duration and cost of search. Saxenian (1994) and Gregory (1984) document how workers change jobs frequently in Silicon Valley without having to relocate. Workers can learn about job openings at social gatherings where they sometimes even receive job offers. One direct effect of clustering, therefore, ought to be an increase in productivity arising from a reduction in unemployment. But, how clustering with its concomitant increase in search efficiency impacts on the openness

\textsuperscript{28}The effects of wealth constraints on efficiency have been recognized in other settings (e.g. Aghion and Tirole (1994) and Lewis and Sappington (2001).

\textsuperscript{29}Aghion and Tirole (1994) similarly find that the researcher gains more control over innovation and that the process becomes more efficient as his bargaining power increases.
of research agreements is unclear. The effect of an increase in $\alpha$, on research arrangements (row 2 of Table 1) is summarized in the following observation.

Observation 4: As search efficiency increases, $E$’s relative bargaining power increases, and research agreements become more open. Engineers become more mobile as a result of the increased search efficiency and the more open work environment. Total surplus and engineer surplus increase, while firm surplus decreases.

When engineers are relatively scarce, these effects arise because $E$’s outside options grow relative to $F$’s as search becomes more efficient. In effect, as employment markets become more efficient, the duration of unemployment for engineers shrinks toward zero whereas the duration for firms declines to a positive number. Increases in search efficiency enhance $E$’s relative bargaining power permitting him to obtain a more open research arrangement. This increases overall efficiency and total surplus as well as the surplus $E$ commands, while decreasing the firm’s total surplus. An important implication of Observation 4 is that clustering not only reduces downtime of inactive firms and unemployed engineers, it also leads to greater mobility of engineers which further increases productive efficiency.

3.2. Quality of Match Information

The likelihood that the researcher’s talents are a good match for the firm is an important factor in the design of research arrangements. The quality of the match varies according to the accuracy and quality of the information which is exchanged in the market. Match quality is likely to be high when firms and employees cluster, permitting frequent exchange of information about product development. Match quality also varies with the maturity of the industry and whether new product research is more applied than basic. In young industries, like computers, software, and medical equipment, it will be more difficult for a firm to predict the evolution of the market and its short-run needs. As such it will be more difficult to predict how the firm will use
the researcher’s innovation. This will be especially true in new industries undergoing changes in consumer demand, formation of strategic alliances, and adoption of product standards and protocols. By contrast, in mature industries with established products, it is more likely that the firm’s research needs will be better defined, and more applied. Often research will be directed to cutting the firm’s supply cost for a specific product.

In industries where the potential applications and outcomes for research are easier to predict, our model indicates that the parties will accommodate an increased likelihood of good matches $\lambda$ by further opening their research arrangements (see row three of Table 1).

Observation 5: When the likelihood of a good initial match increases, the likelihood of $E$ separating from the firm decreases, ceteris paribus. As a consequence, $F$ designs a more open arrangement. Information flow is encouraged and employees are afforded greater mobility. Innovation becomes more efficient, and firm and engineer surpluses increase.

When match quality is high, firms face a smaller likelihood of losing their researchers and the IP in which they have invested. The firm collects a greater share of the ex post surplus as a result. $F$ offers a more open arrangement to compensate $E$ for a reduction in its ex post share of surplus.

This finding is consistent with the high rate of innovative activity that often arises with the clustering of production in a geographic region.\textsuperscript{30} With clustering of production, information about new product development improves. This results in better initial matches. As initial match quality improves, innovation becomes more open and poor matches are corrected with greater probability. Opening of the innovation process reinforces the increased productivity resulting from better initial matches.\textsuperscript{31}

\textsuperscript{30}See, Porter (1990) for industry examples suggesting high innovation resulting from geographic clustering.

\textsuperscript{31}Although we treat $\lambda$ as exogenous, firms can (and do) change the match prob-
Better initial matches also result as technology matures in an industry. Thus, a slowing of innovation, normally associated with “maturity” of technology, may be partly countered by an increase in the efficiency of research.

In addition to the contractual response described in Observation 5, we would expect firms to make structural adjustments to increase the quality of their research matches. Firms that produce a variety of complementary products will enjoy better matches than firms that specialize. An innovation will have greater application for a firm that produces a variety of products. In this way, a vertically integrated firm with both upstream and downstream applications is more likely to benefit from innovation.

3.3. Retention of Knowledge

Openness of research agreements is affected by legal provisions for the protection of intellectual property. Our analysis provides for two varieties of knowledge retention. The first is the ability of $F$ to appropriate value from an innovation when $E$ leaves the firm. In this instance the strength of intellectual property retention is measured by $\varepsilon$ the share of innovation value $\pi^I$ captured by $F$ in the absence of the inventor. $F$’s ability to unilaterally capture returns from innovation will increase when the firm acquires a working knowledge of the engineer’s research. The firm may require $E$ to record and document his research results, or to transfer his knowledge to other firm employees. Also, carefully documenting the engineer’s activities during his employment better enables $F$ to prevent $E$ from departing with IP that was financed by $F$.

The effects of greater retention of knowledge as reflected in a higher $\varepsilon$ (row 4 of Table 1) are summarized by,

**Observation 6:** An increase in $\varepsilon$ enables $F$ to appropriate a

ability by allowing star researchers freedom to pursue their own projects (see, e.g., “The Real Meaning of Empowerment” Economist 3/25/00). Such actions might be used in part to make individual adjustments to a more general openness policy.
greater share of the surplus resulting from inside matches. As a result, the employment agreement becomes more open and efficient and the surpluses of both parties increase.

The intuition for this finding is that cash constraints become less acute when $F$ is able to appropriate a greater share of the surplus. As a result, $F$ offers a more open contract. The effect of making the contract more open is to increase efficiency and the aggregate surpluses of both parties.

The second type of knowledge retention afforded the firm is the ability to retain control of the innovation in instances where the innovation is best developed outside the firm. The extent of this control is measured by $\gamma$ which is influenced by the legal environment as discussed earlier. The impact of endowing $F$ with strong IP control over innovation that is best developed outside the firm (row 5 of Table 1) is summarized by

**Observation 7:** In equilibrium, an increase in $\gamma$ has no effect on the effective degree of contract openness.

When $\gamma$ increases, $F$ maintains the same degree of mobility for $E$ by increasing the probability of $E$ becoming informed about outside opportunities. That is, an increase in $\gamma$ is exactly offset by an increase in $\mu$ so as to maintain the same amount of overall mobility. This neutrality result emerges because the economic effect of both $\mu$ and $\gamma$ is to change the probability that an employee will leave the firm. Thus, when explaining the openness of innovation, it is im-

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32 Relaxing the binary $\gamma$ assumption, for example, by allowing the original employer to have a patent that can be circumvented for a cost, gives the original employer additional ex post bargaining leverage. This leverage translates into a higher ex ante expected payoff to the (old) employer and a lower ex ante expected payoff to the employee for the exit option. Because this leverage would be anticipated in recruitment, we speculate that this sharing of the expected benefit of an efficient departure will force the research environment to be even more open because ex ante bargaining still requires that the employee get his appropriate expected share of the joint downstream payoff.

33 Based on interviews conducted with semiconductor industry managers Ziedon-
important to account for the flow of information across firm boundaries, including both social and professional institutions as noted by Saxenien (1994) and legal institutions (e.g., no-compete clauses and trade secret enforcement) as described in Gilson (1998) and Hyde (1998).

It is easy to see that an endogenous $\gamma$ could be a policy substitute for $\mu$. But what actions can a firm take to make a credible commitment to a smaller $\gamma$, that is, one that permits more mobility? Firms can commit by developing a reputation for not litigating possible infringements of its IP rights when employees leave the firm. The maintenance of such a reputation becomes a hostage against aggressive ex post use of legal remedies to prevent mobility. Hyde (1998) and Gilson (1998) note that job candidates are favorably influenced by these reputations. Saxenien (1994) finds that some firms not only fail to litigate against former employees, but often do business with them and leave the door open for a possible return. In other cases, firms are loathe to hire ex-employees of firms with litigious and/or vindictive reputations.

3.4. Product Life Cycles

How are research arrangements tailored to product longevity? For instance, are open innovation agreements more or less likely to exist in immature industries where innovation is rapid and the rate of product

nis (2000, p. 20) suggests that “if patent rights were weaker, firms would rely more heavily on trade secrets...this would require firms to monitor the activities of employees more closely and to curb the flow of information both within and across firm boundaries.” Her evidence is roughly consistent with our argument for the substitutability of information flow and IP control.

Firms may also commit to “less effective” control of an employee’s IP by giving employees more freedom to work on projects to their own liking. A number of Gregory’s [1984] interviewees, for example, describe how software company projects were modified to fit the interests of workers that firms wished to keep. Finally, it is possible for the firm to assign codifiable IP property rights so as to make employee departure with valuable IP less difficult. However, because it is quite difficult to contract over general IP, effective IP rights assignment appears to be an extreme case.
Observation 8 summarizes the implications of our model regarding product life cycles (row 6 of Table 1).

*Observation 8:* Research agreements will be more open for products with a short life cycle. Although research arrangements will become more efficient, the shorter life span for commercial products will generally reduce the total surplus generated, as well as the surpluses of E and F.

The explanation for Observation 8 is that when new products become obsolete more quickly, both the firm and the engineer are returned to the unemployment pool more often. When labor is in short supply, the engineer has a higher relative expected payoff than F while in the unemployment pool. As the rate of obsolescence increases, the unemployment state becomes more important in determining total surplus for each party. Thus E’s outside option increases relative to F’s endowing E with greater bargaining power to effect a more open research arrangement.

The software industry with its relatively short product cycle, shortage of engineers and high employee turnover appears to conform to the conditions and conclusions posited in Observation 8. However, we are cautious in posing the possibility that high product obsolescence is the cause of an open research environment and high labor mobility. Conceivably, it is the open research environments that maximize the potential for diffusion of knowledge and innovation that produces short product life cycles.

4. An Alliance Interpretation

Throughout this paper we have discussed openness in terms of lowering organizational boundaries which increases an engineer’s contact with outside firms. The policy variable $\mu$ can also be interpreted as a measure of the extent of alliance involvement. That is, as a firm increases the number of its alliances, it increases the likelihood that an employee will find a better outside match (with an alliance partner).
While this interpretation of $\mu$ seems reasonable, it is not apparent that one should treat $\mu$ as endogenous as the decision to engage in alliances involves many factors not modeled here. In contrast, where in the base interpretation one might think that $\gamma$, the intellectual property control parameter that acts as an economic substitute for $\mu$ with respect to employee departure, is given more by the legal environment than chosen by the firm, in an alliance setting $\gamma$ would seem to be more controllable by the firm. This is because the underlying alliance involves a bilateral contract in which intellectual property rules can be directly negotiated and for which employee mobility is likely to be an important consideration.\footnote{As discussed earlier, IP control can be endogenous downward by the extent to which a firm decides to actively enforce its IP rights. Hence, IP control could be treated as a choice variable, though the scope for choice will be limited by the legal environment.}

Thus, most of the observations above would still apply. One implication of Observation 7 in the alliance context is that firms with more alliances would, ceteris parabus, negotiate and enforce stricter intellectual property control than would firms with fewer alliances.

Alliances also seem likely to increase the value that an innovating firm will ultimately receive when an engineer departs to a partner as some of the benefits gained by the partner will flow back to the original firm. Along these lines, an innovating firm can earn a greater return from its investment in R&D if it can make ex ante arrangements to license IP to alliance partners. Unfortunately, difficulties in contracting for the future transfer of IP limit the feasibility of this approach.

5. Conclusion

This paper offers an incomplete contracting explanation for why employers adopt open research arrangements that allow valued employees to depart to another firm. Facilitation of employee mobility increases dissemination of knowledge which feeds innovation and eco-
nomic growth. Many of the factors that increase mobility such as efficient placement markets and better matching are the felicitous results of geographic concentration of firms. Other factors such as a relative worker shortage and a shorter product life cycle are characteristics of rapidly growing industries. Our analysis suggests an explanation for why particular industrial structures and geographic clusters are self-reinforcing and it provides a general lens through which to see how labor markets, innovation, and industrial clusters interact.

6. Appendix

6.1. Comparative Static Predictions

The comparative static predictions indicating how equilibrium variables will respond to changes in the market environment are indicated in Table 1.

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Table 1: Comparative Statics Predictions

The endogenous variables in Table 1 are

\[\text{The notation } -, + \text{ means the comparative static is negative for small values of the exogenous variable and positive for larger values of the exogenous variable.}\]
\( \mu = \) probability of learning about outside match

\( \sigma^O = (1 - \gamma)\mu(1 - \lambda) \), probability of separation

\( V_E = E's \) unemployment surplus

\( V_F = F's \) unemployment surplus

\( S = S_E + S_F, \) total surplus

\( S_E = P_E\rho_E V_E + (1 - \rho_E)P_E W_E \)

\( E's \) total surplus

\( S_F = \rho_F V_F + (1 - \rho_F)W_F \)

\( F's \) total surplus

The exogenous variables are

\( P_E = \) Relative supply of engineers

\( \alpha = \) Search efficiency

\( \lambda = \) Likelihood of suitable match

\( \varepsilon = F's \) retention of surplus

\( \gamma = F's \) likelihood of restricting mobility

\( \delta = \) Rate of product obsolescence

6.2. Derivation of Equilibrium

The full environment in which \( E \) and \( F \) operate is described by the vector \( \vec{m} = (P_E, \alpha, \lambda, \varepsilon, \gamma, \delta; | B, \pi_L, \pi_H) \subset R^9 \). The first six entries of \( \vec{m} \) are the exogenous variables of primary interest we have identified in the text. The remaining three variables complete our specification of the environment. For a given environment \( \vec{m} \), an efficient open-constrained equilibrium exists provided the following conditions are satisfied. First, the labor market must be in equilibrium. This requires that the number of employed workers be equal to the number of engaged firms at all times, and that the rate of new matches created equal the rate of termination of existing matches.

\[
(1 - \rho_E^*) = (1 - \rho_E^*)P_E \\
\alpha\rho_F^*\rho_E^*P_E = (1 - \rho_F^*)\delta
\]

where \( \rho_E^*(\alpha, \delta, P_E) \) and \( \rho_F^*(\alpha, \delta, P_E) \) are the equilibrium unemployment rates for \( E \) and \( F \), respectively.
In addition, the efficient open-constrained equilibrium requires that the value functions for $E$ and $F$ satisfy

$$V_E = \alpha \rho_E^* BW_E + B (1 - \alpha \rho_F^*) V_E$$

$$V_F = \alpha \rho_F^* P_E BW_F + B (1 - \alpha \rho_E^* P_E) V_F.$$  

The expected surplus from matching for $E$ and $F$ are respectively $W_E$ and $W_F$ where

$$W_E = \sigma_H^* Y^I_E(\pi_H) + \sigma_L^* Y^I_E(\pi_L) + \sigma^O Y^O_E(\pi_H)$$

$$W_F = \sigma_H^* Y^I_F(\pi_H) + \sigma_L^* Y^I_F(\pi_L) + \sigma^O Y^O_F(\pi_H)$$

and

$$Y^I_E(\pi_i) = \frac{S(\pi_i) + V_E - (V_F + \varepsilon \pi_i)}{2}$$

$$Y^O_E(\pi_H) = S(\pi_H) - V_F$$

$$Y^I_F(\pi_i) = \frac{S(\pi_i) + (V_F + \varepsilon \pi_i) - V_E}{2}$$

$$Y^O_F(\pi_H) = V_F$$

$$\sigma_H^* = \lambda, \ \sigma_L^* = (1 - \lambda)(1 - \mu(1 - \gamma)), \ \sigma^O = (1 - \lambda)\mu(1 - \gamma)$$

$$S(\pi_i) = \pi_i + B[(1 - \delta)S(\pi_i) + \delta(V_E + V_F)], \ for \ i = H, L.$$  

The final condition for the efficient open-constrained equilibrium requires that cash transfers, $P$, equal zero and that $E$ and $F$ split the net surplus from a match so that,

$$BW_F(\mu^*) - V_F = BW_E(\mu^*) - V_E$$

where $\mu^* \in (0, 1)$ is the probability that $E$ is informed of an outside match in equilibrium.
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In equilibrium \( \mu^* \) satisfies equations (9)-(21). To determine \( \mu^* \) we first solve for \( V_E \) and \( V_F \) in terms of \( W_E \) and \( W_F \) from equations (11) and (12) to obtain

\[
V_E = k_E BW_E, \quad V_F = k_F BW_F
\]

(22)

where \( k_E = \alpha \rho_F^* / (1 - \alpha \rho_F^*) \) and \( k_F = \alpha \rho_E^* P_E / (1 - \alpha \rho_E^* P_E) \).

Combining equations (21) and (22) allows us to solve for \( W_F \) in terms of \( W_E \) where

\[
W_F = \bar{k}_F W_E
\]

(23)

and \( \bar{k}_F = (1 - k_E) / (1 - k_F) \). From equations (11)-(13), (15), (16), (19), (20), and (23) we can solve for \( W_E \) in terms of \( \mu \) to obtain

\[
W_E = \frac{n_0^E + n_1^E \mu}{d_0^E + d_1^E \mu}
\]

(24)

where

\[
n_0^E = \frac{\lambda}{2} \left( \frac{\pi_H}{1 - B(1 - \delta)} \right) + \frac{1 - \lambda}{2} \left( \frac{\pi_L}{1 - B(1 - \delta)} + \varepsilon \pi_L \right)
\]

\[
n_1^E = (1 - \gamma)(1 - \lambda) \left( \frac{\pi_H}{1 - B(1 - \delta)} \right)
\]

\[
- \frac{(1 - \gamma)(1 - \lambda)}{2} \left( \frac{\pi_L}{1 - B(1 - \delta)} + \varepsilon \pi_L \right)
\]

\[
d_0^E = 1 - \frac{1}{2} \left( \frac{\delta B^2 (k_E + \bar{k}_F)}{1 - B(1 - \delta)} + B (k_E - \bar{k}_F) \right)
\]

\[
d_1^E = (1 - \lambda)(1 - \gamma) \left( \frac{\delta B^2 (k_E + \bar{k}_F)}{2(1 - B(1 - \delta))} - B k_F \bar{k}_F - B (k_E - \bar{k}_F) \right).
\]
Similarly, employing equations (11), (12), (14), (17)-(19), (22), and (23) we can get an alternative expression for $W_E$

$$W_E = \frac{n_0^F + n_1^F \mu}{d_0^F + d_0^F \mu}$$

where

$$n_0^F = \frac{\lambda}{2} \left( \frac{\pi_H}{1 - B(1 - \delta)} - \varepsilon \pi_H \right) + \frac{1 - \lambda}{2} \left( \frac{\pi_L}{1 - B(1 - \delta)} - \varepsilon \pi_L \right)$$

$$n_1^F = \frac{(1 - \gamma)(1 - \lambda)}{2} \left( \frac{\pi_L}{1 - B(1 - \delta)} - \varepsilon \pi_L \right)$$

$$d_0^F = \frac{k_F - \lambda}{2} \left( \frac{\delta B^2 (k_E + k_F)}{1 - B(1 - \delta)} + B (k_F - k_E) \right)$$

$$d_1^F = (1 - \lambda)(1 - \gamma) \left( -k_F^{-} k_F^{-} + \frac{1}{2} \left( \frac{\delta B^2 (k_E + k_F^{-})}{1 - B(1 - \delta)} + B (k_F^{-} - k_E) \right) \right).$$

In equilibrium the two expressions for $W_E$ in (24) and (25) must be equal. This requires that we find the equilibrium probability, $\mu^*$ such that

$$\frac{n_0^F + n_1^F \mu}{d_0^F + d_0^F \mu} = \frac{n_0^E + n_1^E \mu}{d_0^E + d_0^E \mu}$$

or simplifying and rewriting terms

$$Z(\mu^*, \bar{m}) = a(\bar{m}) \mu^* + b(\bar{m}) \mu^* + c(\bar{m}) = 0$$

where the constant coefficients, $a(\bar{m})$, $b(\bar{m})$, and $c(\bar{m})$ all depend on the market environment, $\bar{m}$, and are given by

$$a(\bar{m}) = n_1^F d_0^E - n_0^E d_1^F$$

$$b(\bar{m}) = n_1^F d_0^E + n_0^E d_1^F - n_0^E d_0^F - n_1^E d_1^F$$

$$c(\bar{m}) = n_1^F d_1^E - n_1^E d_1^E.$$
An equilibrium exists provided there is a real root $\mu^* \in (0, 1)$ satisfying (26).

It is straightforward to verify that there is a subset of environments $\bar{m} \subset R^9_+$ for which an efficient open-constrained equilibrium exists. Whenever an equilibrium exists it is unique, as there is a single real root in $(0, 1)$, denoted by $\mu^*(\bar{m})$ satisfying (26). The comparative statics predictions reported in Table 1 for $\mu$ are straightforward, though tedious, calculations of

$$\frac{d\mu^*}{dm_i} = -\frac{Z_{e,i}(\mu^*, e)}{Z_{\mu}(\mu^*, e)}$$

for $m_i = P_E, \alpha, \lambda, \gamma, \delta$, and $\varepsilon$. The predictions for the other endogenous variables of interest including $\sigma^O, V_E, V_F, S, S_E$, and $S_F$ which are all functions of $\mu^*$, are readily derived from (27).

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