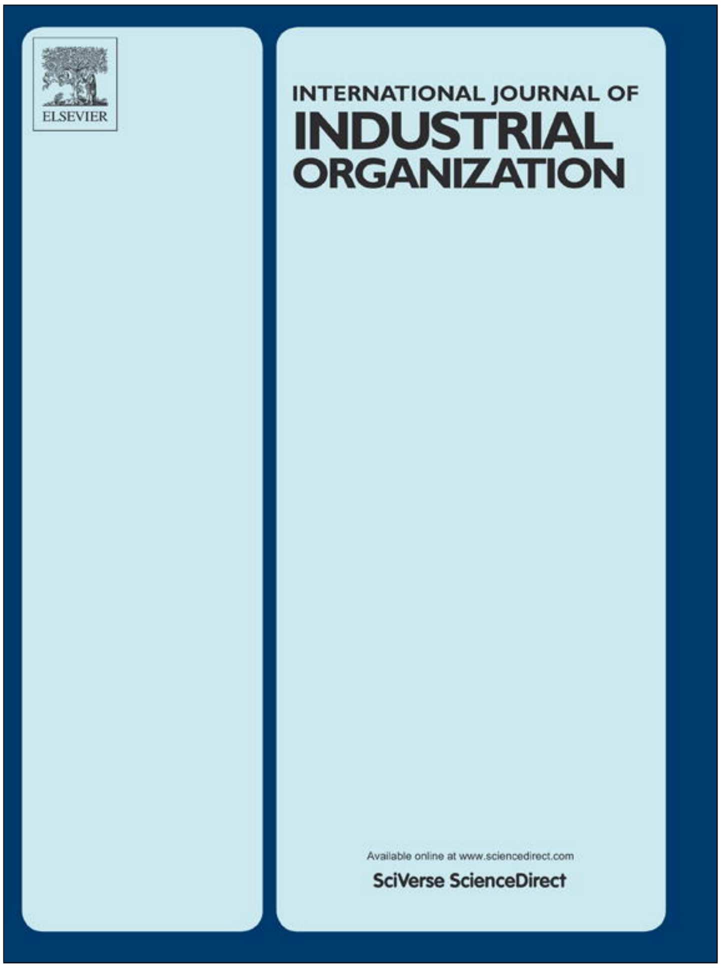

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Tacit knowledge with innovative entrepreneurship ☆

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ABSTRACT

Tacit knowledge affects the trade-off between entrepreneurship and technology transfer. I present a formal model in which an inventor and the existing firm engage in a strategic innovation game by choosing whether to compete or to cooperate through technology transfer. The model highlights how the problem of tacit knowledge affects the inventor's R&D investment and the existing firm's investment in absorptive capacity. The inventor's tacit knowledge implies that benefits from own-use through entrepreneurship can exceed the benefits from technology transfer. In equilibrium, higher-quality inventions result in entrepreneurship and lower-quality inventions result in technology transfer. R&D investment and absorption investment are strategic substitutes in the innovation game with the option of entrepreneurship. The possibility of entrepreneurship increases R&D investment and reduces absorption investment. The equilibrium probability of entrepreneurship is decreasing in the costs of R&D, increasing in the costs of absorption, and decreasing in the set-up costs of new firms.

1. Introduction

Inventors' *tacit knowledge* can make it difficult to separate discoveries from the individuals who make them. Although both inventors and adopters *know that* a discovery has particular features, some inventors *know how* to apply their discoveries better than do potential adopters. Inventors can benefit from their tacit knowledge by becoming innovative entrepreneurs who establish firms to implement their discoveries. However, entrepreneurship entails costs of setting up new firms and rent dissipation from competing with existing firms. Alternatively, inventors can transfer their discoveries to existing firms but this entails costs of codifying, transferring, and absorbing tacit knowledge and imperfect implementation of discoveries.[1] Therefore, tacit knowledge creates a fundamental trade-off between own-use of discoveries by their inventors and adoption of discoveries by others. To address this trade-off, I present a formal model that examines how inventors' tacit knowledge influences the choice between innovative entrepreneurship and technology transfer. The option of innovative entrepreneurship changes the market for discoveries and affects inventors' investment in research and development (R&D) and potential adopters' investment in absorption of discoveries.

The economic analysis of tacit knowledge presented here highlights the important role of the individual inventor. The individual inventor's tacit knowledge is essential for implementing technology. Tacit knowledge gives an *own-use advantage* to inventors who become innovative entrepreneurs in comparison with technology transfer to existing firms. This result contrasts with the standard view that complementary assets give existing firms an advantage in implementing technology.[2] Tacit knowledge creates problems for technology transfer that differ from the effects of adverse selection, moral hazard, and imperfect intellectual property (IP) protections. Tacit knowledge affects incentives for endogenous investments in knowledge production and absorption and provides incentives for innovative entrepreneurship.

The main insight is that the *marginal* returns to R&D are greater with innovative entrepreneurship than with technology transfer to an existing firm. An inventor's own-use of a discovery through innovative

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[1] By its very nature, tacit knowledge may not be transferable to others unless it is converted to explicit knowledge. Generating explicit knowledge based on tacit knowledge entails various economic costs. An inventor seeking to transfer tacit knowledge must first attempt to codify the knowledge in explicit form, including written documents, technical descriptions, mathematics, diagrams, blueprints, computer code, and prototypes. Next, the individual seeking to transfer tacit knowledge must communicate with the receiver through messages, discussions, teaching, training, and other means. Finally, the receiver must devote time, effort, and resources to absorb the transferred knowledge, including research and development (R&D), education, training, and acquisition of equipment. Transferring tacit knowledge entails explicit costs of education, training, consulting, scholarly publications, and information services. Taken together these costs represent *absorption investment*.

[2] Teece (1986, 1988) shows that IP problems induce firms to internalize R&D and emphasizes the importance for technology transfer of the complementary assets of established firms, such as IP, human capital, marketing channels, see also Teece (2006) and Gans and Stern (2003).

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entrepreneurship generates greater marginal returns than adoption by the existing firm for two reasons. First, due to the inventor's tacit knowledge, the marginal returns to own-use of the invention are greater than the returns obtained by the existing firm. Second, due to creative destruction, an innovative entrepreneur who competes with an existing firm offers a lower price and sells more output than the incumbent, thus increasing the returns to the invention. Therefore, tacit knowledge and creative destruction have reinforcing effects. An inventor who anticipates becoming an innovative entrepreneur invests more in R&D than an inventor who anticipates technology transfer.

The main results of the analysis are as follows. First, I show that tacit knowledge implies that higher-quality inventions result in entrepreneurship and lower-quality inventions result in technology transfer. Second, I show that even though investments in R&D and absorptive capacity are complements in technology transfer, they can be strategic substitutes in the innovation game with the option of entrepreneurship. An inventor who anticipates greater absorptive capacity reduces R&D effort and an existing firm that anticipates more R&D investment reduces absorption investment. Third, I show that introducing the option of innovative entrepreneurship increases R&D investment and lowers absorption investment. Finally, I find that the equilibrium probability of entrepreneurship is decreasing in the costs of R&D, increasing in the costs of technology transfer, and decreasing in the set-up costs of new firms. Because the inventor and the existing firm choose between cooperation and competition, I show that the likelihood of technology transfer is correspondingly increasing in the costs of R&D, decreasing in the costs of technology transfer, and increasing in the set-up costs of new firms.

An inventor's tacit knowledge is a fundamental aspect of the process of discovery as well as subsequent diffusion of economic innovations. The development of light-emitting diodes (LEDs) illustrates the importance of the individual inventor and tacit knowledge. Shuji Nakamura invented blue, green, and white LEDs and the blue laser and developed extensive tacit knowledge about how to manufacture LEDs.[3] In a classic example, Collins (1974) examined the transfer of knowledge about the Transversely Excited Atmospheric Pressure CO_2 (TEA) Laser. Collins, (1974, p. 183) found that "the unit of knowledge cannot be abstracted from the 'carrier.' The scientist, his culture and skill are an integral part of what is known" (see also Ravetz, 1971). The inventor develops tacit knowledge through observations of complex research processes and outcomes. The inventor's tacit knowledge is also the product of personal experiences, training, insights, creativity, and capabilities rather than organizational capital, routines, or culture.[4]

The philosopher Bertrand Russell (1911, p. 120) distinguishes between knowledge by acquaintance and knowledge by description and points out that "our judgment is wholly reduced to constituents with which we are acquainted."[5] The psychology and sociology literatures further develop the concept of tacit knowledge (Cowan et al., 2000). Polanyi (1962, 1967) draws a distinction between tacit and explicit knowledge; see also Ryle (2002) on the difference between knowing-how and knowing-that. Sociologists Rogers (1962) and Coleman (1964) examine the imperfect diffusion of innovations. Citing the sociology literature, Arrow (1969) observes that "Different communication channels have different costs (or equivalently different capacities), where these costs include the ability of the sender to "code" the information and the recipient to "decode" it." Machlup's (1962) landmark study estimates that the combined costs of producing and distributing knowledge constitute nearly 30 per cent of the U.S. economy.

The closest paper to the present analysis is that of Gans and Stern (2000).[6] They observe that "under the traditional assumptions of the literature on technological competition, and in the absence of noncontractible information asymmetries between the incumbent and entrant, observations of entry by the startup into the product market represent something of an economic puzzle" (Gans and Stern, 2000, p. 487). Gans and Stern (2000) consider a three-stage model in which there is an R&D race between an incumbent and a potential entrant in the first stage. If the incumbent wins the race, the incumbent remains a monopolist, and if the entrant wins the race, the incumbent and entrant engage in bargaining in the second stage, with either technology licensing or entry occurring in the third stage. Gans and Stern (2000, p. 487) introduce a property rights or spillover parameter and allow the incumbent to continue to invest in R&D during the bargaining stage that may be used to "expropriate the entrant's rents from successful innovation." Therefore, the incumbent considers the startup's R&D a strategic substitute for the incumbent's in-house research. The present model differs from Gans and Stern (2000) in a number of ways. In my model, only the inventor engages in R&D, not the incumbent firm, which highlights the role of tacit knowledge. In my model, the incumbent firm cannot expropriate the inventor's discovery so that the inventor has property rights to the invention. Gans and Stern (2000, 2002, 2003) do not address tacit knowledge. The value added of the present work is that the inventor's tacit knowledge generates benefits from own-use of the discovery, which affects R&D investment, absorption investment, the quality of invention, the quality of technology transfer, and entrepreneurship.

The analysis of tacit knowledge is related to some problems of imperfect knowledge transmission in organizations (Dessein and Santos, 2006; Dewatripont, 2006). A question in models of organization is whether tasks should be centralized or decentralized depending on the trade-off between imperfect coordination among two agents and the advantages of division of labor. This is related to our analysis, in which the inventor and the existing firm choose whether to cooperate or to compete, depending on the trade-offs between knowledge transfer and own-use of knowledge. This allows the endogenous formation of organizations through the choice between contracts for technology transfer to the existing firm and the establishment of a new firm that competes with the existing firm.

The present model of tacit knowledge helps to explain empirical observation of inventors participating in the innovation process, joining new ventures as entrepreneurs or employees. Zucker et al. (1998b) consider the early entrants into biotechnology and the new biotech units of existing firms. They show that the location and timing of usage of the new technology are "primarily explained by the presence at a particular time and place of scientists who are actively contributing to the basic science as represented by publications reporting genetic-sequence discoveries in academic journals."[7] Particular innovations are closely tied to the complementary knowledge and capabilities of individual "star scientists." Zucker et al. (2002b) find that for "breakthrough discoveries where scientific productivity becomes relevant to commercialization, the labor of the most productive scientists is the main resource around which firms are built or transformed."[8] Their empirical results on "star scientists" in biotech suggest that inventors in that industry who have

[3] Nakamura won the 2006 Millennium Technology Prize for his invention of blue, green, and white LEDs and the blue laser. See Nakamura et al. (2000) and Johnstone (2007).

[4] Spender (1996) elaborates on the distinction between individual psychological tacit knowledge and social collective tacit knowledge that is shared among individuals. Spender (1994) also distinguishes between individual and collective knowledge that is explicit and argues that different types of knowledge generate different economic rents. Many organizational studies have elaborated on the notion of tacit knowledge in groups, see Sandelands and Stablein (1987), Weick and Roberts (1993), and Nonaka and Takeuchi (1995).

[5] Russell (1911, p. 117) states that "The fundamental epistemological principle in the analysis of propositions containing descriptions is this: Every proposition which we can understand must be composed wholly of constituents with which we are acquainted" (see also Russell, 2000).

[6] See also Gans et al. (2002) and Gans and Stern (2003).

[7] Zucker et al. (1998a, 1998b, p. 290)

[8] See also Zucker and Darby (2001) for a study of Japan's star scientists in biotech, Zucker et al. (1998a) on star scientists in US biotech, and Zucker et al. (2002a) on the economic value of the "tacit knowledge" of star scientists.

tacit knowledge will tend to become entrepreneurs or to work closely with firms that apply the transferred technology. Entrepreneurs bring capabilities that are complementary resources for the new firm (Alvarez and Busenitz, 2001). Ancori et al. (2000) argue that an individual's knowledge is based on his cognitive abilities, see also Nightingale (1998) and Pozzali and Viale (2006).

The present model of tacit knowledge accords with empirical observations that codification, communication, and absorption of tacit knowledge are determined endogenously. Cohen and Levinthal (1989) empirically estimate the effect of firms' R&D investment on their absorptive capacity for publicly-available information. Cowan and Foray (1997) discuss codification of knowledge and absorptive capacity. Cowan and Jonard (2003) model the connection between absorptive capacity and learning difficulties and examine the extent to which knowledge is either codified or tacit. Ancori et al. (2000) distinguish between knowledge and information and explore how information is the codification of tacit knowledge. Balconi et al. (2007) emphasize that codification of knowledge is a matter of degree that depends on the information content of the codification and the extent to which other individuals can comprehend and use the information, see also Johnson et al. (2002).

The paper is organized as follows. Section 2 presents a basic model of tacit knowledge in an innovation game with entrepreneurship and technology transfer. Section 3 characterizes the equilibrium of the innovation game with tacit knowledge. Section 4 extends the basic model of tacit knowledge to a market with differentiated products. Section 5 considers some limitations and extensions of the present model. Section 6 concludes the discussion.

2. The Model

This section introduces a three-stage model of strategic interaction between an inventor and an existing firm. In the first stage, the inventor chooses R&D investment and an existing firm chooses investment in absorptive capacity. In the second stage, the inventor's discovery is realized and observed by both the inventor and the existing firm. The inventor and the existing firm choose whether to cooperate or to compete. If the inventor and the existing firm choose to cooperate, they form a contract to transfer the new technology from the inventor to the existing firm. If the inventor and the existing firm choose to compete, the inventor becomes an entrepreneur and establishes a firm. In the third stage, the market reaches equilibrium. If the inventor and the existing firm contracted to transfer technology, the existing firm operates as a monopolist using the new technology and observes absorptive capacity. If the inventor and the existing firm did not choose to cooperate, the new firm established by the innovative entrepreneur enters the market and displaces the existing firm through competition.

2.1. The inventor

Let $c_1>1$ represent the existing firm's initial production cost with the existing technology. An inventor invests z in uncertain R&D at a cost of kz. The new technology, c_2, is given by the knowledge production function,

$$c_2 = t(z,\ x), \tag{1}$$

which depends on R&D investment z and a random variable x.[9] The random variable, x, is an input to the knowledge production function that represents scientific and technological uncertainty. The random variable has a cumulative probability distribution $F(x)$ on the nonnegative real line, with nonnegative continuous density $f(x)$. The inventor's investment in R&D is chosen before the random variable is realized.

[9] On the knowledge production function, see Griliches (1979).

The knowledge production function, $t(z, x)$, is normalized so that it takes values in $[0, 1]$ and is differentiable and decreasing in z and x, $\partial t(z, x)/\partial z = t_z(z, x)<0$ and $\partial t(z, x)/\partial x = t_x(z, x)<0$. Let $t(z, 0) = 1$ for all z and let unit costs approach zero as the R&D shock, x, becomes large, $\lim_{x\to\infty} t(z, x) = 0$. The ratio $\frac{t_z(z,x)}{t_x(z,x)}$ is the marginal rate of technical substitution (MRTS) of R&D investment, z, for the shock, x. This is the amount that R&D investment must be reduced for an increase in the shock for the resulting new technology, c_2, to be kept constant. Assume that R&D investment, z, is a normal input, which is equivalent to assuming that the MRTS is increasing in the shock, x.

We define a property of the density function of the R&D shock that will be used to characterize the equilibrium.[10]

Definition 1. *The density function $f(x)$ is well-behaved if the product of the density function and the MRTS is non-decreasing in x for all z,* $\frac{d\ln f(x)}{dx} \geq -\frac{\partial}{\partial x}\ln\left(\frac{t_z(z,x)}{t_x(z,x)}\right)$.

The density function $f(x)$ is well-behaved whenever it is increasing or constant because the MRTS is increasing in x. For example, the density function is constant for the uniform distribution and increasing for the Pareto (or Power Law) distribution. The density function $f(x)$ also is well-behaved if it does not decrease too rapidly. For example, the exponential distribution has a decreasing probability density, $f(x) = \lambda e^{-\lambda x}$, where $\lambda>0$. Suppose that the production function has a normalized Cobb-Douglas form, $t(z, x) = (1+z^{\gamma}x^{1-\gamma})^{-1}$, so that $\frac{\partial}{\partial x}\ln\left(\frac{t_z(z,x)}{t_x(z,x)}\right) = \frac{\partial}{\partial x}\ln\left(\frac{\gamma}{1-\gamma}\frac{x}{z}\right) = 1/x$. Then, the exponential density function is well-behaved if the parameter is not too large, $\lambda \leq 1/x$. The density also is well-behaved if it is non-monotonic but does not decrease too rapidly. For example, consider the truncated normal distribution defined for $x\geq 0$ with parameters μ and σ, and let the production be normalized Cobb-Douglas. Then, the distribution is well-behaved for x such that $(x-\mu)/\sigma^2 \leq 1/x$.

Market demand for the final product, $D(p)$, is a twice continuously differentiable and decreasing function of the final product price, p. The profit of a monopoly firm with price p and costs c equals

$$\Pi(p, c) = (p - c)D(p). \tag{2}$$

Assume that the profit function is concave in price. The profit-maximizing monopoly price, $p^M(c)$, is unique and increasing in cost c and initial profits equal

$$\Pi^M(c) = \Pi\left(p^M(c),\ c\right). \tag{3}$$

Monopoly profit is decreasing and convex in cost c, $\Pi^{M\prime}(c) = -D(p^M(c))<0$ and $\Pi^{M\prime\prime}(c) = -D'(p^M(c))p^{M\prime}(c)>0$.

The inventor can transfer the new technology to the existing firm or become an entrepreneur and apply the technology. If the inventor chooses to become an entrepreneur, the inventor has the tacit knowledge to successfully apply the new technology, c_2. To enter the product market, the inventor incurs entry costs, $K>0$. The new firm enters the market and competes with the existing firm. The entrant and the incumbent offer homogeneous products and engage in Bertrand–Nash price competition. Entrepreneurship results in creative destruction, that is, the entrant displaces the incumbent, because $c_2 \leq 1 < c_1$. The results extend to Bertrand competition with differentiated products, where the entry of new firms reduces the profits of existing firms but incumbent firms may survive.

Applying Arrow's (1962) terminology, an invention is *drastic* if the entrant's monopoly price at the new technology is less than or equal to the existing firm's unit cost, $p^M(c_2) \leq c_1$. With a drastic invention,

[10] This property of the product of the density function and the MRTS is related to the properties of the "critical ratio" that was introduced by Poblete and Spulber (2012) in an agency setting. The "critical ratio" is the product of the hazard rate of the shock and the MRTS.

the entrant chooses the monopoly price and eliminates the incumbent because the monopoly price at the new technology is less than the incumbent's unit cost. The entrepreneur earns the full monopoly profit using the new technology, $\Pi^M(c_2)$. An invention is *non-drastic* if the entrant's monopoly price at the new technology is greater than the initial unit cost, $p^M(c_2)>c_1$. With a non-drastic invention, the entrant is constrained by the incumbent firm's technology and prices at the incumbent's unit cost, again eliminating the incumbent. Combining the two possibilities, the entrant's price equals

$$p^*(c_2,\ c_1) = \min\left\{p^M(c_2),\ c_1\right\}. \tag{4}$$

The entrepreneur's profits are written as $\Pi^E(c_2)=\Pi(p^*(c_2,\ c_1),\ c_2)$, suppressing the initial cost c_1. This represents dissipation of economic rents because of creative destruction.[11] The profits of the newly established firm equal the costs of a competitive entrant net of set up costs, $\Pi^E(c_2)-K$.

Assume that very high realizations of the R&D shock generate drastic inventions, $p^M(0)<c_1$. Also, assume that very low realizations of the R&D shock generate non-drastic inventions, $p^M(1)>c_1$. This implies that the entrant earns lower profits than a monopolist using the new technology due to both entry costs and competition with the incumbent, $\Pi^E(1)-K<\Pi^M(1)$. To simplify the discussion, assume that entry is profitable with a non-drastic invention, $\Pi^E(1)-K>0$. This allows the discussion to focus on the trade-off between entrepreneurship and technology transfer. Then, profit from innovative entrepreneurship equals

$$\pi^E(c_2) = \Pi^E(c_2) - K. \tag{5}$$

Notice that the entrepreneur's profit with a non-drastic invention, $\Pi^E(1)-K$, may be greater than or less than monopoly profits at the existing technology, $\Pi^M(c_1)$.

2.2. The existing firm

The inventor's *tacit knowledge* is the *know-how* needed to apply the new technology, c_2. This means that after R&D takes place, the new technology, c_2, is commonly observable but imperfectly transferable. The inventor and the existing firm are symmetrically informed about the quality of the new technology. Although both the inventor and the existing firm *know that* the new technology is c_2, the existing firm does not have the *know-how* to apply the invention so that technology transfer between the inventor and the existing firm is imperfect. The representation of tacit knowledge presented here can be embedded in many different types of R&D models.

The existing firm invests b in building its *know-how* to improve the quality of technology transfer at a cost of hb. The existing firm's absorption rate is given by the production function

$$a = a(b,\ y), \tag{6}$$

where y is a random variable with cumulative probability distribution $G(y)$ on the nonnegative real line, with nonnegative and finite continuous density $g(y)$. The absorption rate $a(b, y)$ is nonnegative, differentiable and increasing in b and y, and $\int_0^\infty a(b,y)\mathrm{d}G(y) < 1$. Some investment is necessary for absorption, $a(0, y)=0$ for all y.

If the inventor transfers the technology to the existing firm, the transfer is imperfect due to tacit knowledge. The absorption rate determines the existing firm's costs after adopting the new technology,

$$c = a(b,y)c_2 + (1-a(b,y))c_1. \tag{7}$$

The imperfect transfer of knowledge to the existing firm, $c>c_2$, is an *implicit* cost of transferring technology. The outcome of the game would not be affected by explicit costs, so such costs are normalized to zero without affecting the discussion. The representation of imperfect knowledge transfers is very general. The knowledge transfer formulation in Eq. (7) is sufficiently general to include situations in which there is no uncertainty about the absorption rate and the transferred technology is simply of lower quality than the discovery, $a(b, y)=a(b)<1$ for all y.[12] Then, the existing firm can be viewed as choosing the quality of the technology that will be implemented. The formulation also includes situations in which the new technology is implemented by the existing firm with some probability of success, so that $a(b,y)=1$ for $y\geq y(b)$ and $a(b,y)=0$ otherwise. Then, the existing firm can be viewed as choosing the probability of successful technology transfer, $1-F(y(b))$.[13]

The existing firm's absorption investment, b, is chosen before the new technology, c_2, is observed and before the shock, y, is realized. The existing firm does not observe the shock y until after the new technology is implemented. So, for any new technology, c_2, the existing firm's expected profits equal

$$\pi^M(b,c_2) = \int_0^\infty \Pi^M[a(b,y)c_2 + (1-a(b,y))c_1]\mathrm{d}G(y). \tag{8}$$

Assume that at the best invention, $c_2=0$, monopoly profits net of entry costs exceed monopoly profits with technology transfer, $\Pi^M(0)-K>\pi^M(b,\ 0)$. Therefore, because $p^M(0)<c_1$ implies that $\Pi^E(0)=\Pi^M(0)$, the profits from innovative entry for sufficiently high realizations of x exceed monopoly profits at the existing technology, $\pi^E(0)>\pi^M(b,\ 0)$.

2.3. The three-stage game

The timeline for the three-stage game is as follows. At the start of stage one, the inventor chooses R&D investment, z, and the existing firm chooses absorption investment, b. Then, the new technology, $c_2=t(z,\ x)$, is commonly observed at the end of the first stage. In the second stage, the inventor and the existing firm chose whether to compete or to cooperate through technology transfer. In the third stage of the game, if technology transfer occurs, the existing firm observes the absorption rate, $a(b,y)$, and engages in production. If entrepreneurship occurs, the new firm enters the market and competes with the existing firm.

Define the *net return from the inventor's own use of tacit knowledge through entrepreneurship*,

$$\Gamma(b,\ c_2) = \pi^E(c_2) - \pi^M(b,\ c_2). \tag{9}$$

This is the return to entrepreneurship using the new technology net of the return from technology transfer to the existing firm. The benefits of own-use of tacit knowledge are reduced by the costs of setting up a new firm and the rent dissipation from creative destruction. The returns

[11] If the invention is drastic, the entrant earns monopoly profits, $\Pi(p^*(c_2,\ c_1),\ c_2)=\Pi^M(c_2)$. If the invention is non-drastic, the entrant's profits are constrained by competition with the incumbent, $\Pi(p^*(c_2, c_1), c_2)<\Pi^M(c_2)$.

[12] The imperfect transmission of knowledge can be interpreted as an implicit cost in which only a fraction of tacit knowledge reaches its destination, that is, knowledge is lost in transmission. This corresponds to the representation of transportation costs in international trade as a reduction in the quantity or quality of the good being shipped. Transporting ice is costly because it melts away so that only a fraction of ice reaches its destination ("only a fraction of ice exported reaches its destination as unmelted ice," Samuelson, 1954, p. 268).

[13] In the economics of organizations, for example, Dessein and Santos (2006) assume that an organization chooses the probability that a worker successfully learns a task from another worker, which they interpret as the quality of communication.

to technology transfer are the opportunity costs of own-use of tacit knowledge. Increased investment in absorption by the existing firm increases the benefits of technology transfer and thus reduces the net return from own use of tacit knowledge.

The inventor and the existing firm will choose to compete if and only if the net return from own-use of tacit knowledge is non-negative, $\Gamma(b, c_2) \geq 0$. If the inventor and the existing firm choose to compete, then (in the third stage) the inventor earns $\pi^E(c_2)$. The existing firm exits the market when products are homogeneous. The existing firm may continue to operate when products are differentiated as will be seen in a later section. If the inventor and the existing firm choose to cooperate, then in the third stage the inventor earns a royalty, R, and does not enter the market, and the existing firm applies the new technology and earns expected profits, $\pi^M(b, c_2) - R$.[14]

The inventor and the existing firm bargain over the royalty payment for the new technology in the second stage.[15] R&D costs and knowledge transfer costs are sunk costs when bargaining occurs. Without loss of generality, suppose that the outcome of bargaining is given by Nash bargaining. The royalty, R, is contingent on the quality of the technology transfer. The inventor's threat point in bargaining equals the post-entry profits as an entrepreneur net of the costs of setting up a new firm. The existing firm's threat point equals zero because if the firm and the inventor do not cooperate, the inventor becomes an entrepreneur and establishes a new firm that displaces the existing firm. When products are differentiated, the post-entry profits of the existing firm affect the royalty as will be shown in a later section. The investment costs of R&D and absorption do not affect the outcome of bargaining because investment decisions are made before bargaining takes place, hence these costs are sunk. Therefore, for any new technology, c_2, the expected royalty is

$$R(b, c_2) = (1/2)\pi^M(b, c_2) + (1/2)\pi^E(c_2). \tag{10}$$

After technology transfer takes place, the existing firm's absorption rate $a(b, y)$ is realized, which determines the existing firm's costs and the royalty payment to the inventor.

In the first stage of the game, the inventor and the existing firm choose investment levels. The inventor and the existing firm play a noncooperative game because investments in R&D and absorptive capacity are not contractible.[16] Denote the Nash equilibrium by (z^*, b^*). The inventor chooses R&D investment, z, to maximize expected profit,

$$\begin{aligned} z^* = \arg\max_z \Big\{ & E\left[\pi^E(c_2) \middle| \pi^M(b^*, \ c_2) \leq \pi^E(c_2)\right] \\ & + E\left[R(b^*, \ c_2) \middle| \pi^M(b^*, \ c_2) > \pi^E(c_2)\right] - kz \Big\}, \end{aligned} \tag{11}$$

where $c_2 = t(z, x)$. The existing firm chooses absorption investment, b, to maximize expected profit,

$$b^* = \arg\max_b \left\{ E\left[\pi^M(b, \ c_2) - R(b, \ c_2) \middle| \pi^M(b, \ c_2) > \pi^E(c_2)\right] - hb \right\}, \tag{12}$$

where $c_2 = t(z^*, x)$ and expectations are taken over the R&D shock x.

[14] Any explicit technology transfer cost paid by the inventor would be equivalent to a reduction in the cost of establishing a firm. Suppose that T is an explicit transfer cost. Then, the inventor's net return is $R - T - (\Pi^E(c_2) - K) = R - [\Pi^E(c_2) - (K - T)]$. Therefore, T can be normalized to zero without any loss of generality.

[15] The bargaining game between the inventor and the existing firm can be recast as an alternating offer bargaining game in which there is a unique subgame perfect equilibrium that depends on the discount factors of the two parties (Rubinstein, 1982).

[16] Contracting problems have been widely studied in general settings. See Spulber (2002, 2009) for an overview and discussion and see Grout (1984) and Grossman and Hart (1986) on incomplete contracting.

3. Equilibrium of the strategic innovation game

This section examines the equilibrium of the strategic innovation game. The equilibrium is fully described by R&D investment, z, and absorption investment, b, which are determined in the first stage and the choice between technology transfer and entrepreneurship in the second stage. The three-stage game is solved by backward induction. The third stage has already been fully described by the reduced form profit and royalty functions.

3.1. The choice between competition and cooperation

After the inventor chooses R&D investment, z, and the existing firm chooses absorption investment, b, the choice between cooperation and competition in the second stage depends on the realization of the shock, x. Recall that entrepreneurship occurs if and only if $\Gamma(b, c_2) \geq 0$. We now show that the marginal return to R&D is greater for an entrepreneurial firm than it is for an existing firm receiving a technology transfer. This means that regardless of whether applying tacit knowledge through entrepreneurship generates a net benefit or loss, the marginal net return to R&D investment, $(\partial/\partial z)\Gamma(b, c_2)$, is always positive. The following result establishes an important single-crossing condition that is useful for analyzing the equilibrium of the innovation game.

Lemma 1. *An increase in R&D investment increases the net return from own-use of tacit knowledge,*

$$\frac{\partial \Gamma(b, c_2)}{\partial z} = \Gamma_c(b, c_2) t_z(z, x) > 0. \tag{13}$$

Proof. For $\pi^E(c_2) > 0$,

$$\Gamma_c(b, c_2) = \left\{ \Pi^{E\prime}(c_2) - \int_0^\infty \Pi^{M\prime}[a(b, y)c_2 + (1 - a(b, y))c_1] a(b, y) dG(y) \right\}. \tag{14}$$

By the envelope theorem, $\Pi^{E\prime}(c_2) = -D(p^*(c_2, c_1))$ and $\Pi^{M\prime}(c) = -D(p^M(c))$. Because of imperfect transmission of tacit knowledge, it follows that $c \geq c_2$, where the inequality is strict for some values of y. Therefore, because the monopoly price is increasing in unit cost, $p^M(c) \geq p^M(c_2)$, and competition between the entrant and the incumbent lowers the price, $p^M(c_2) \geq p^*(c_2, \ c_1)$. Downward-sloping demand implies that

$$D\left(p^M(c)\right) \leq D\left(p^M(c_2)\right) \leq D(p*(c_2, \ c_1)).$$

It follows that $-\Pi^{M\prime}(c) \leq -\Pi^{\prime E}(c_2)$ and strictly greater for some values of y. Therefore,

$$\Gamma_c(b, c_2) \leq \Pi^{E\prime}(c_2)\left[1 - \int_0^\infty a(b, y) \mathrm{d}G(y)\right] < 0$$

so that $t_z(z, x) < 0$ implies $\Gamma_c(b, c_2) t_z(z, x) > 0$. □

Because the new technology, $t(z, x)$, is decreasing in the shock, x, it also follows that an increase in the R&D shock x also increases the net returns from own-use of tacit knowledge, $(\partial/\partial x)\Gamma(b, \ c_2) = \Gamma_c(b, \ c_2) t_x(z, x) > 0$.

The result holds because both competition and tacit knowledge increase incentives for R&D investment. First, competition increases R&D investment because the marginal benefit from cost-reducing R&D is proportional to market demand, i.e. the marginal profit from cost reduction equals the firm's demand. Demand is greater under entrepreneurship than it is for an incumbent with technology transfer because the new firm competes with the incumbent firm, which strictly lowers prices when the invention is drastic in comparison to the incumbent's cost.[17] Second, tacit knowledge increases R&D investment because imperfect transfer of knowledge to the incumbent firm increases the costs of the existing firm in comparison to unit costs with own-use of new technology. This in turn increases the monopoly price charged by the existing firm in comparison to the monopoly price at the costs corresponding to own-use of the new technology. The higher price lowers the demand for the output of the existing firm in comparison to a monopolist with own-use of the new technology. The inventor's own-use of tacit knowledge generates greater marginal returns than a transfer of knowledge to the incumbent firm.

With homogeneous products, competition increases the marginal return to cost reductions for the entrant because of a price reduction effect, $-\Pi^{M\prime}(c_2) \leq -\Pi'^{E}(c_2)$. This contrasts with Vives' (2008) model in which the demand-reducing effect of entry outweighs the price-reducing effect of competition on each firm's output. With differentiated products, competition reduces the marginal return to cost reduction for each firm when all firms remain in the market. However, the result in Lemma 1 does not depend on Bertrand competition with homogeneous products, as will be seen in the subsequent discussion of differentiated products competition.

Lemma 1 implies a *single-crossing property* that is important for our analysis, see Fig. 1. Lemma 1 shows that the derivative of the return to entrepreneurship, $\pi^E(c_2)$, with respect to the R&D shock, x, is greater than that of the return to technology transfer, $\pi^M(b, c_2)$, where both functions are increasing in the R&D shock. If $\pi^E(t(z, 0)) < \pi^M(b, t(z, 0))$, the curve representing $\pi^E(c_2)$ crosses the curve representing $\pi^M(b, c_2)$ at most once from below. By assumption, $\pi^E(0) > \pi^M(b, 0)$, so that the two curves cross at some x^*. At this critical value, the net return to own-use of tacit knowledge equals zero,

$$\Gamma(b, \ t(z, \ x^*)) = 0. \tag{14}$$

The net return to own-use of tacit knowledge is such that $\Gamma(b, t(z, x)) > 0$ for $x > x^*$ and $\Gamma(b, t(z, x)) < 0$ for $x < x^*$. If, on the other hand, $\pi^E(t(z, 0)) \geq \pi^M(b, t(z, 0))$, let $x^*(b, z) = 0$. In this case, note that $\pi^E(c_2) \leq \pi^M(b, c_2)$ for all x. By continuity and the intermediate value theorem, the following result holds.

Lemma 2. *There exists a unique critical value of the R&D shock, $x^*(b, z)$, that is finite and nonnegative for any b and z. The net return to own-use of tacit knowledge, $\Gamma(b, t(z, x^*))$, equals zero if $x^*(b, z)$ is positive and is positive if $x^*(b, z) = 0$. Entrepreneurship occurs if and only if $x \geq x^*(b, z)$.*

The single-crossing property has the following implication. With tacit knowledge, inventors with higher quality inventions, $x \geq x^*(b, z)$, become entrepreneurs and inventors with lower quality inventions, $x < x^*(b, z)$, transfer their technology to the existing firm.

When the critical value of the R&D shock is positive, it has the following properties by Lemma 1 and Eq. (14). The critical value is decreasing in R&D investment,

$$\frac{\partial x^*(b,z)}{\partial z} = -\frac{t_z(z,x^*)}{t_x(z,x^*)} < 0.$$

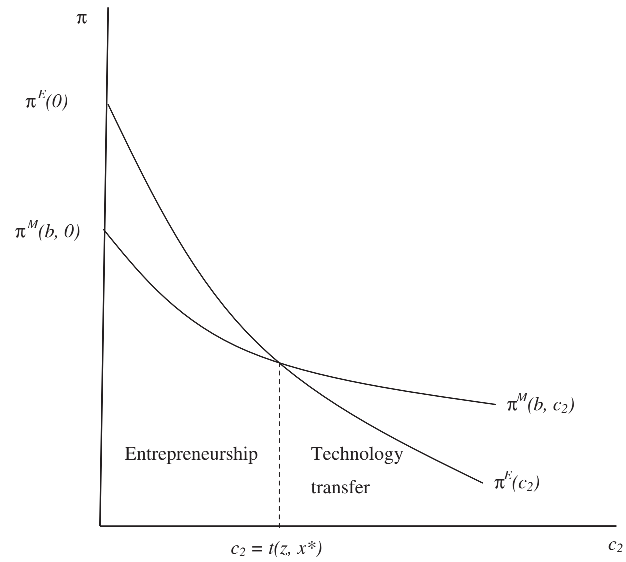

Fig. 1. The critical value of the new technology determines whether the outcome of the innovation game is entrepreneurship or technology transfer.

The critical value is increasing in absorption investment,

$$\frac{\partial x^*(b,z)}{\partial b} = \frac{\pi_b{}^M(b,c_2)}{\Gamma_c(b,c_2)t_x(z,x^*)} > 0.$$

[18]

Also, the critical value is increasing in the entrepreneur's setup costs, K,

$$\frac{\partial x^*(b,z)}{\partial K} = \frac{1}{\Gamma_c(b,c_2)t_x(z,x^*)} > 0.$$

3.2. Strategic investment in R&D and absorption

This section characterizes the first stage of the strategic innovation game. To establish some benchmarks, define the R&D investment of an inventor who expects with certainty to become an innovative entrepreneur,

$$z^E = \arg\ \max_z E\pi^E(c_2) - kz.$$

If the existing firm expects entrepreneurship with certainty, the firm will not invest in absorption, $b^E = 0$. Also, define the R&D investment of an innovative monopoly firm,

$$z^M = \arg\ \max_z E\Pi^M(c_2) - kz.$$

Finally, define the Nash equilibrium R&D investment and absorption investment when the inventor and the existing firm expect technology transfer with certainty,

$$z^T = \arg\ \max_z ER\left(b^T, \ t(z, \ x)\right) - kz,$$
$$b^T = \arg\ \max_b E\left[\pi^M\left(b, \ t\left(z^T, \ x\right)\right) - R\left(b, \ t\left(z^T, \ x\right)\right)\right] - hb.$$

[17] This extends Arrow's (1962) result that downstream competition in the product market increases incentives to invent relative to those for monopolist, that is, $\Pi^M(c_2) - \Pi^M(c_1) \leq \Pi(p^*(c_2, c_1), c_2)$. The present result is at the margin rather than being due to the monopolist's inertia.

[18] From Eq. (8), the marginal expected profit of absorption investment for the monopolist receiving the transfer is positive,

$$\pi_b{}^M(b,c_2) = \int_0^\infty \Pi^{M\prime}[a(b,y)c_2 + (1-a(b,y))c_1]a_b(b,y)dG(y)(c_2 - c_1) > 0.$$

When technology transfer occurs with certainty, R&D investment, z, and absorption investment, b, are *strategic complements*,

$$\frac{\partial^2}{\partial b \partial z}\left[\int_0^\infty R(b,c_2)\mathrm{d}F(x) - kz\right] > 0$$
$$\frac{\partial^2}{\partial b \partial z}\left[-(1/2)\int_0^\infty \Gamma(b,c_2)\mathrm{d}F(x) - hb\right] > 0.$$

R&D investment induces more investment in absorptive capacity and vice versa. This is because R&D investment and absorption investment are complements in technology transfer, $\pi^{M}{}_{bc}(b, c_2)t_z(z, x) > 0$.[19]

The expected marginal return to R&D effort for the innovative entrepreneur is greater than that for either the inventor expecting to transfer the technology or the innovative monopolist. This implies that an innovative entrepreneur would invest more in R&D than either an inventor transferring technology or a monopoly firm.

Proposition 1. *An innovative entrepreneur chooses more R&D investment than an inventor expecting technology transfer, $z^E \geq z^T$, and more R&D investment than a monopoly firm, $z^E \geq z^M$.*

Proof. By Lemma 1, $(d/dz)[\pi^E(c_2) - R(b, c_2)] = (1/2)(d/dz)\Gamma(b, c_2) > 0$, so that $z^E \geq z^T$, for all b. By similar arguments, $(d/dz)[\pi^E(c_2) - \Pi^M(c_2)] > 0$, so that $z^E \geq z^M$. □

Given the critical value of the shock $x^*(b, z)$ and the form of the royalty, we can characterize the objective functions for the inventor and the existing firm. The expected net benefits of the inventor and the existing firm are

$$U(b,z) = \int_0^{x^*(b,z)} R(b,c_2)\mathrm{d}F(x) + \int_{x^*(b,z)}^\infty \pi^E(c_2)\mathrm{d}F(x) - kz, \tag{15}$$

$$V(b,z) = \int_0^{x^*(b,z)} \left[\pi^M(b,c_2) - R(b,c_2)\right]\mathrm{d}F(x) - hb, \tag{16}$$

where $c_2 = t(z, x)$. A Nash equilibrium is defined by $z^* = \arg\max_z U(b^*, z)$ and $b^* = \arg\max_b V(b, z^*)$.

Substituting for the royalty function, the expected net benefits of the inventor and the existing firm can be written using the net return from own-use of tacit knowledge,

$$U(b,z) = -(1/2)\int_0^{x^*(b,z)} \Gamma(b,c_2)\mathrm{d}F(x) + \int_0^\infty \pi^E(c_2)\mathrm{d}F(x) - kz, \tag{17}$$

$$V(b,z) = -(1/2)\int_0^{x^*(b,z)} \Gamma(b,c_2)\mathrm{d}F(x) - hb, \tag{18}$$

where $c_2 = t(z, x)$. Using the form of the critical value of the shock, the marginal returns to R&D investment and to absorption investment are

$$U_z(b,z) = \int_0^\infty \pi^{E\prime}(c_2)t_z(z,x)\mathrm{d}F(x) - (1/2)\int_0^{x^*(b,z)} \Gamma_c(b,c_2)t_z(z,x)\mathrm{d}F(x) - k, \tag{19}$$

$$V_b(b,z) = (1/2)\int_0^{x^*(b,z)} \pi_b{}^M(b,c_2)\mathrm{d}F(x) - h. \tag{20}$$

The following proposition characterizes the Nash equilibrium of the innovation game. The inventor chooses R&D effort in equilibrium that is less than or equal to the effort chosen by an inventor who anticipates entrepreneurship with certainty. The proposition is important because it demonstrates the connection between tacit knowledge and entrepreneurship.

Proposition 2. (i) *There is a unique Nash equilibrium such that R&D investment is $z^* = z^E > 0$, there is no absorption investment, $b^* = 0$, and entrepreneurship always occurs in equilibrium, $x^* = 0$, if and only if $\Pi^M(c_1) \leq \Pi^E(1) - K$.* (ii) *Nash equilibrium R&D investment and absorption investment are such that $z^* \leq z^E$ and $b^* > 0$ and either entrepreneurship or technology transfer can occur in equilibrium, $x^* > 0$,* if and only if *$\Pi^M(c_1) > \Pi^E(1) - K$.*

The proof appears in Appendix A. The necessary and sufficient condition for technology transfer to be possible in equilibrium is for monopoly profit at the existing technology to be greater than the return to entrepreneurship at the lowest realization of the shock. Because we have fully characterized the Nash equilibrium for the situation in which technology transfer cannot occur, we now restrict attention to the situation in which both entrepreneurship and technology transfer can occur in equilibrium, $\Pi^M(c_1) > \Pi^E(1) - K$.

When the inventor has the option of applying tacit knowledge through entrepreneurship, we will show that under fairly general conditions R&D investment and absorption investment are *strategic substitutes*. The intuition for this result is that in the innovative game with tacit knowledge, R&D investment and absorption investment affect the relative likelihood of technology transfer versus entrepreneurship. Recall that R&D investment and absorption investment are strategic complements when technology transfer occurs with certainty. Therefore, the option of entrepreneurship changes the technology transfer game, so that the inventor invests *less* in R&D when expecting a higher absorption investment and the existing firm invests *less* in absorption when expecting a higher R&D investment.

Proposition 3. *If $f(x)$ is well-behaved on $[0, x^*(b, z)]$ for all z and b, then R&D investment, z, and absorption investment, b, are strategic substitutes, $U_{zb}(b, z) = V_{zb}(b, z) < 0$.*

The proof appears in Appendix A. The condition that $f(x)$ is well-behaved is a sufficient condition but not a necessary condition. The result holds even if the product of the density and the MRTS is decreasing as long as it does not decrease too rapidly.[20]

The next proposition illustrates the importance of the strategic substitutability of R&D investment, z, and absorption investment, b. By making these investments strategic substitutes, the option of entrepreneurship raises R&D investment and lowers absorption investment in comparison with the situation with only technology transfer. The proof of the following proposition appears in Appendix A and uses the reaction functions that are shown in Fig. 2.

Proposition 4. *At a Nash equilibrium of the innovation game when R&D investment, z, and absorption investment, b, are strategic substitutes, R&D investment is greater than with certain technology transfer, $z^* > z^T$, and absorption investment is lower than with certain technology transfer, $b^* < b^T$.*

Propositions 2 and 4 show that in the investment game where the inventor has the option of entrepreneurship, Nash equilibrium investment strategies z^* and b^* take values in compact intervals, $[0, z^E]$ and $[0, b^T]$ respectively. The intuition for this result is as follows. The inventor invests more in R&D in anticipation of possibly using that knowledge as an entrepreneur because of higher marginal returns to invention under competition and because own-use avoids imperfect knowledge transfers. The existing firm invests less in absorption than with certain technology transfer because of the substitution effect of higher R&D investment by

[19] Absorption investment and unit costs are substitutes for the existing firm, $\pi_{bc}{}^M(b,c_2) =$
$\int_0^\infty \left\{\Pi^{M\prime\prime}[a(b,y)c_2 + (1-a(b,y))c_1]a(b,y)a_b(b,y)\mathrm{d}G(y)(c_2-c_1) + \frac{\pi_b{}^M(b,c_2)}{(c_2-c_1)} < 0\right.$, This expression is less than zero because profit is convex in costs and $c_2 < c_1$.

[20] The result holds if $f(x)$ satisfies $\frac{f(0)-f(x*)}{f(0)} \leq \frac{\pi_b{}^M(b,t(z,0))}{\pi_b{}^M(b,t(z,x*))}$. Because the MRTS is increasing, this implies that $\frac{t_z(z,0)}{t_x(z,0)}f(0) - \frac{t_z(z,x*)}{t_x(z,x*)}f(x*) \leq \frac{\pi_b{}^M(b,t(z,0))}{\pi_b{}^M(b,t(z,x*))}\frac{t_z(z,0)}{t_x(z,0)}f(0)$. Integrating $U_{zb}(b, z)$ by parts yields

$$U_{zb}(b,\theta) = (1/2)\left[\int_0^{x*(b,z)} \pi_b{}^M(b,t(z,x))\left[-\frac{\partial}{\partial x}\left(\frac{t_z(z,x)}{t_x(z,x)}f(x)\right)\right]\mathrm{d}x - \pi_b{}^M(b,t(z,0))\frac{t_z(z,0)}{t_x(z,0)}f(0)\right].$$

For $x < x^*$, $t(z, x) > t(z, x^*)$, so that $\pi^M{}_{bc}(b, c) < 0$ implies $\pi_b^M(b, t(z, x)) < \pi_b^M(b, t(z, x^*))$. Given $\frac{t_z(z,x)}{t_x(z,x)}f(x)$ decreasing, the restriction on $f(x)$ implies that $U_{zb}(b, z) < 0$.

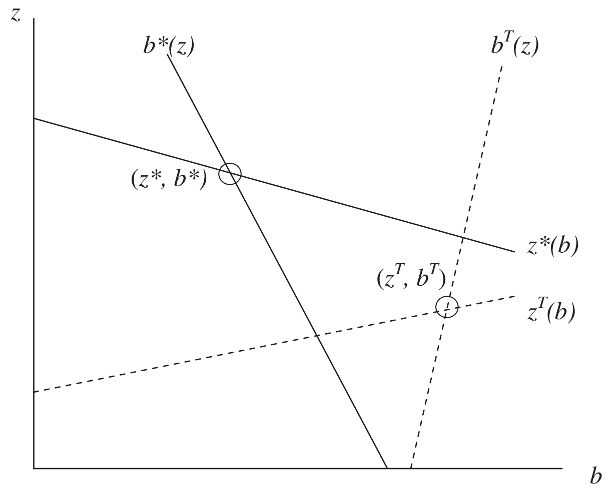

Fig. 2. Comparison of the Nash equilibrium of the investment game when the inventor has the option of entrepreneurship, (z^*, b^*), with the Nash equilibrium of the investment game with certain technology transfer, (z^T, b^T).

the inventor if the technology is transferred and the possibility that the technology will not be transferred.

The game in investment strategies satisfies the conditions for a smooth supermodular game (Milgrom and Roberts, 1990). There may be multiple Nash equilibria and there exist smallest and largest pure Nash equilibria. In the statement of the following propositions, a Nash equilibrium (z^*, b^*) refers to both the smallest and the largest Nash equilibra, (z_L^*, b_L^*) and (z_H^*, b_H^*), where $z_L^* \geq z_H^*$ and $b_L^* \leq b_H^*$. The proofs appear in Appendix A and apply monotone comparative statics analysis; see Topkis (1998) and Milgrom and Roberts (1990, 1994).

When investments in R&D and absorption are strategic substitutes, the costs of R&D investment and absorptive investment have opposite effects on equilibrium strategies.

Proposition 5. *When R&D investment, z, and absorption investment, b, are strategic substitutes, the following hold. Equilibrium R&D investment, z^*, is decreasing in the costs of R&D, k, and increasing in the costs of absorption investment, h. Equilibrium absorption investment, b^*, is increasing in the costs of R&D, k, and decreasing in the costs of technology transfer, h. Also, the probability of entrepreneurship, $1 - F(x^*)$, is decreasing in the costs of R&D, k, and increasing in the costs of absorption investment, h.*

The costs of R&D and the costs of absorptive effort affect the critical value of the shock only indirectly through equilibrium strategies. More costly R&D, which directly affects the production of knowledge, makes entrepreneurship less likely by reducing the net returns to own-use as well as technology transfer. More costly absorptive effort, which directly affects knowledge transfers, makes entrepreneurship more likely. Also, patenting of business method inventions should provide better access to information about inventions, which may also reduce costs of transferring knowledge (Spulber, 2011a).

When investments in R&D and absorption are strategic substitutes, the costs of setting up a new firm affect R&D investment and absorption investment in opposite ways.

Proposition 6. *When R&D investment, z, and absorption investment, b, are strategic substitutes, the following hold. Equilibrium R&D investment, z^*, is decreasing in the set-up costs of a new firm, K, and equilibrium absorption investment, b^*, is increasing in the set-up costs of a new firm, K. Also, when x^* is interior, the probability of entrepreneurship, $1 - F(x^*)$, is decreasing in the set-up costs of a new firm, K.*

The costs of setting up a firm increase R&D investment because of the returns to own-use of tacit knowledge but decrease absorption investment, in part because R&D investment and absorption investment are strategic substitutes. Set-up costs increase the critical level of the shock both directly and indirectly by affecting equilibrium strategies, thus reducing the likelihood of entrepreneurship. The set-up costs of new firms are likely to vary across industries. This helps to explain variations across industries of the proportion of inventors choosing to transfer technology versus becoming entrepreneurs, see Jensen and Thursby (2001) and Zucker et al. (2002b).

The analysis thus far has not considered R&D by the incumbent firm. Suppose that the incumbent firm can conduct R&D to reduce its costs c_1 prior to the start of the strategic game and suppose that the independent inventor then improves on the incumbent's technology, $c_1 > c_2$. It can be shown that the net return from own-use of tacit knowledge is increasing in the incumbent's initial cost,

$$\frac{\partial \Gamma(b, c_2)}{\partial c_1} = \frac{\partial \pi^E(c_2)}{\partial c_1} - \frac{\partial \pi^M(b, c_2)}{\partial c_1} > 0.$$

This is because the entrepreneur's profit $\pi^E(c_2)$ increasing in the incumbent's initial cost when the independent inventor makes a non-drastic invention and otherwise does not depend on the incumbent's initial cost. Also, the return from technology transfer, $\pi^M(b, c_2)$, is increasing in the incumbent's initial cost. It follows that incumbent R&D to lower costs c_1 reduces the net return from own-use of tacit knowledge by the independent inventor and raises the critical value of the R&D shock,

$$\frac{\partial x^*(b, z)}{\partial c_1} = -\frac{\partial \Gamma(b, c_2)}{\partial c_1} \frac{1}{\Gamma_c(b, c_2) t_x(z, x^*)} < 0.$$

Incumbent R&D to lower costs c_1 thus reduces the likelihood of entrepreneurship for given investment levels by increasing the critical value, x^*. Incumbent R&D to lower costs c_1 would increase the R&D investment of an inventor anticipating entrepreneurship because $\frac{\partial^2 E\pi^E(c_2)}{\partial c_1 \partial z} < 0$. The effects of the lower costs c_1 on the inventor's equilibrium R&D and the incumbent firm's absorption investment are indeterminate.

4. Product differentiation

This section considers the problem of tacit knowledge with product differentiation. Market demand is derived from the preferences of a representative consumer with quadratic utility,

$$U(q_1, q_2) = 2q_1 + 2q_2 - (1/2)(q_1)^2 - (1/2)(q_2)^2 - sq_1q_2, \tag{21}$$

where the substitution parameter s is such that $0 \leq s < 1$. The existing firm supplies good q_1 at price p_1 and the entrant supplies good q_2 at price p_2. The demand functions are $D_i(p_1, p_2)$, $i = 1, 2$. The analysis of the Bertrand–Nash equilibrium in this section draws upon Zanchettin (2006).[21] Assume that the incumbent monopolist is viable with the initial technology, $c_1 < 2$, so the monopolist also is viable with the new technology.[22] We maintain all of the earlier assumptions for the monopoly case.[23]

[21] Although we focus on the quadratic utility case, the properties of the profit and price functions hold more generally. For additional discussion of the class of utility functions that yield similar properties for comparative statics analysis of a duopoly equilibrium, see Milgrom and Roberts (1990). For differentiated duopoly with symmetric costs, see Singh and Vives (1984), and for differentiated duopoly with asymmetric costs and qualities, see Zanchettin (2006). The analysis can be extended to other differentiated product settings such as Hotelling-type (1929) price competition. The results also can be examined with Cournot quantity competition with differentiated products.

[22] To derive the existing firm's monopoly profit, let $q_2 = 0$. The representative consumer's utility function implies that $U(q_1, 0) = 2q_1 - (1/2)(q_1)^2$. The consumer's demand for the incumbent's product is $D_1(p_1) = 2 - p_1$. The monopoly price is $p^M(c) = (2 + c)/2$ and monopoly profit equals $\Pi^M(c) = (p^M(c) - c)D_1(p^M(c)) = (2 - c)^2/4$.

[23] Recall that $\Pi^M(0) - K > \pi^M(b, 0)$ and $\Pi^E(1) - K > 0$. Note that $p^M(0) < c_1$ holds because $p^M(0) = 1$. The assumption $p^M(1) > c_1$ requires $c_1 < 3/2$.

Let $\Pi_1(c_1, c_2)$ represent the incumbent's profits after entry, and let $\Pi_2(c_1, c_2)$ represent the entrant's profits. The incumbent firm and the entrepreneurial entrant engage in Bertrand–Nash price competition with differentiated products. The Bertrand–Nash equilibrium prices $p_1{}^*$ and $p_2{}^*$ solve

$$\Pi_1(c_1, c_2) = \max_{p_1}(p_1 - c_1)D_1(p_1, p_2{}^*) \tag{22}$$

$$\Pi_2(c_1, c_2) = \max_{p_2}(p_2 - c_2)D_2(p_1{}^*, p_2). \tag{23}$$

The equilibrium prices depend on the costs of the two firms and the product differentiation parameter, $p_1{}^*(c_1, c_2)$ and $p_2{}^*(c_1, c_2)$.

The entrepreneur's return from entering the market equals $\pi^E(c_2) = \Pi_2(c_1, c_2) - K$. The existing firm's return from adopting the technology is monopoly profits from technology transfer net of post-entry profits with entry, $\pi^M(b, c_2) - \Pi_1(c_1, c_2)$. With product differentiation, *the net return from the inventor's own use of tacit knowledge through entrepreneurship*, $\pi^E(c_2) - [\pi^M(b, c_2) - \Pi_1(c_1, c_2)]$, thus equals the difference between industry profits after entry and the existing firm's profits with technology transfer,

$$\Gamma(b, c_2) = \Pi_1(c_1, c_2) + \Pi_2(c_1, c_2) - K - \pi^M(b, c_2). \tag{24}$$

Entrepreneurship occurs if and only if the net return to own-use is non-negative, $\Gamma(b, c_2) \geq 0$.

The intensity of product-market competition depends positively on the substitution parameter s and on the new and existing technologies. The industry profits function, $\Pi_1(c_1, c_2) + \Pi_2(c_1, c_2)$, is continuous in the substitution parameter, s, and is continuous and decreasing in the entrant's costs, c_2. The industry profit function has three segments corresponding to the profits of a duopoly, a limit-pricing entrant, and a monopoly-pricing entrant, see Fig. 3. Industry profits are convex in c_2 for the duopoly, linear for the limit-pricing entrant, and convex for the monopoly-pricing entrant.

First, when the entrant's costs are not too low, $c_2 > c_2^0(s, c_1)$, both the entrant and the incumbent operate profitably. The entrant's cost threshold is obtained by setting $q_1 = 0$,

$$c_2{}^0(s, c_1) = 2 - \frac{\left(2 - s^2\right)(2 - c_1)}{s} < c_1. \tag{25}$$

Second, if the entrant's costs are in an intermediate range, $c_2^{00}(s, c_1) < c_2 \leq c_2^0(s, c_1)$, the entrant drives out the incumbent firm with limit pricing and obtains profits $\Pi_2^L(c_1, c_2) = (1/s^2)(2 - c_1)[s(2 - c_2) - (2 - c_1)]$. Third, if the entrant's costs are low, $c_2 \leq c_2^{00}(s, c_1)$, the entrepreneurial entrant drives out the incumbent by offering a monopoly price, $p^M(c_2) = (2 + c_2)/2$ and earns monopoly profits, $\Pi^M(c_2) = (2 - c_2)^2/4$. The lower cost threshold exists only if $c_1 + s > 2$,

$$c_2{}^{00}(s, c_1) = \frac{2(c_1 + s - 2)}{s} < c_2{}^0(s, c_1). \tag{26}$$

This defines a *drastic invention* when products are differentiated.

With differentiated products, the marginal return to R&D is greater for an entrepreneurial firm than it is for an existing firm receiving a technology transfer under some conditions. This result is analogous to Lemma 1. If the new technology is of sufficiently high quality, $c_2 \leq c_2^0(s, c_1)$, the entrant displaces the existing firm either through monopoly pricing or through limit pricing. Then, the price-reducing effect of competition outweighs the demand-reducing effect of competition on output per firm so that competition increases incentives for R&D. If the new technology is of sufficiently low quality, $c_2 > c_2^0(s, c_1)$, then both the entrant and the incumbent operate after entry takes place. The demand-reducing effect of entry tends to outweigh the price-reducing effect of competition on output per firm, which reduces marginal returns

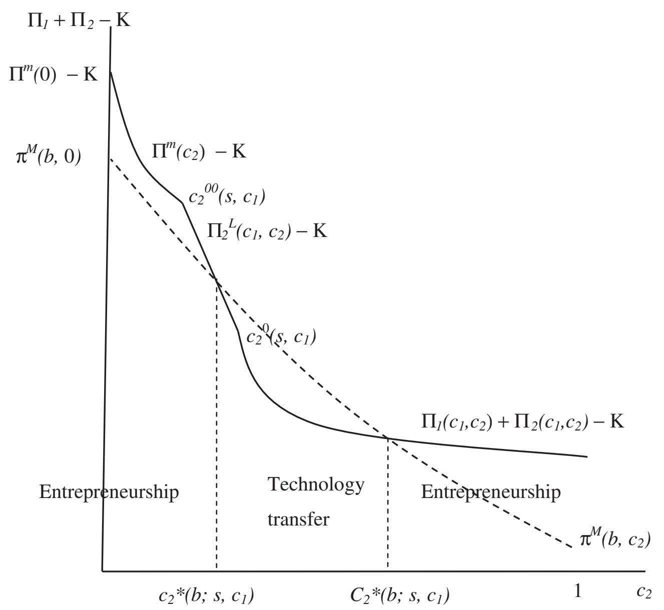

Fig. 3. The outcome of the innovation game is entrepreneurship for low-quality inventions, $c_2 > C_2{}^*(c_1, b)$ or high-quality inventions, $c_2 \leq c_2{}^*(c_1, b)$, and the outcome is technology transfer for intermediate-quality inventions, $c_2{}^*(c_1, b) < c_2 \leq C_2{}^*(c_1, b)$.

to cost-reducing R&D. However, if the absorption rate is low, then an increase in R&D investment increases the net return from own-use of tacit knowledge.

Lemma 3. *With differentiated products, an increase in R&D investment increases the net return from own-use of tacit knowledge,* $\frac{\partial \Gamma(b, c_2)}{\partial z} = \Gamma_c(b, c_2)t_z(z, x) > 0$, *if either (i)* $c_2 \leq c_2^0(s, c_1)$ *or (ii)* $c_2 > c_2^0(s, c_1)$ *and* $\int_0^\infty a(b, y)dG(y) < -\left(1/\Pi^{M'}(c_2)\right)\partial(\Pi_1(c_1, c_2) + \Pi_2(c_1, c_2))/\partial c_2$.

The proof appears in Appendix A. When both firms can operate profitably after entry, an improvement in the new technology, that is a lower c_2, increases the entrant's profit but decreases the post-entry profit of the incumbent firm. Increasing the incumbent's profit raises the net benefit from technology adoption and correspondingly reduces the net return to own-use of tacit knowledge, which is the sum of industry profits net of the profits from technology adoption. In this case, post-entry competition provides a disincentive to R&D.

Compare the present analysis of differentiated products with that of Vives (2008).[24] For a variety of demand models, Vives (2008) shows that entry reduces output per firm because the demand-reducing effect of entry outweighs the price-reducing effect of competition on output per firm when all firms operate in equilibrium. Vives (2008) therefore finds that competitive entry reduces each firm's incentives for internal R&D to reduce costs. In the present model, competition increases incentives to innovate because the entrant has a greater output than an incumbent monopolist when the entrant displaces the incumbent. Then, from Lemma 3 (i), $z^E = \arg\max_z E\Pi_2(c_1, c_2) - K - kz \geq z^M$. Conversely, when both the entrant and the incumbent operate after entry, competition decreases incentives for R&D for the potential entrant in comparison with an incumbent monopolist when $-\partial\Pi_2(c_1, c_2)/\partial c_2 < -\Pi^{M\prime}(c_2)$, which implies that $z^E < z^M$. The incumbent does not conduct R&D in the present model. Investment in R&D by the incumbent would further reduce the entrant's incentives for R&D because –

[24] The economics literature has emphasized the effects of product market competition on R&D by firms that vertically integrate R&D and production (Bester and Petrakis, 1993; Cabral, 2003; Dasgupta and Stiglitz, 1980a, 1980b; Gilbert and Newbery, 1982; Qiu, 1997; Spence, 1984; Vives, 2008). In these studies, competing firms each undertake internal R&D to lower their own costs of production.

$\partial^2 \Pi_2(c_1, c_2)/\partial c_1 \partial c_2 > 0$, so that reducing the incumbent's costs decreases the marginal returns to R&D for the entrant.

Consider now the outcome of the innovation game. We consider the situation in which industry profits with entry exceed the incumbent's profits with technology transfer, evaluating both at the lowest-quality invention. The single-crossing condition in the next result corresponds to Lemma 2 with homogeneous products.

Lemma 4. *With differentiated products, if $\Pi_1(c_1, 1) + \Pi_2(c_1, 1) - K \leq \pi^M(b, 1)$, there exists a unique critical value of the R&D shock, $x^*(b, z)$, that is finite and nonnegative for any b and z. The net return to own-use of tacit knowledge, $\Gamma(b, t(z, x^*))$, equals zero if $x^*(b, z)$ is positive and is positive if $x^*(b, z) = 0$. Entrepreneurship occurs if and only if $x \geq x^*(b, z)$.*

Recall the earlier assumption that $\Pi^m(0) - K > \pi^M(b, 0)$. Then, $\Pi_1(c_1, 1) + \Pi_2(c_1, 1) - K \leq \pi^M(b, 1)$ implies that the curve representing the industry profits function, $\Pi_1(c_1, c_2) + \Pi_2(c_1, c_2) - K$, crosses the curve representing the incumbent's profit function, $\pi^M(b, c_2)$, exactly once from above at $c_2 = c_2^*(b; s, c_1)$. This corresponds to the single-crossing condition that was observed with homogeneous products. There is a critical value of the R&D shock, $x^* = x^*(b, z)$ that solves $t(z, x^*) = c_2^*(b; s, c_1)$. It follows that the net return to the inventor's own-use of tacit knowledge, $\Gamma(b, c_2)$, equals zero at x^* and entrepreneurship occurs when the R&D shock is greater than or equal to x^*.

Consider now the situation in which industry profits with entry are greater than the incumbent's profits with technology transfer, evaluating both at the lowest-quality invention, $\Pi_1(c_1, 1) + \Pi_2(c_1, 1) - K > \pi^M(b, 1)$. Then, there exist two cost thresholds, such that the outcome of the innovation game is entrepreneurship for low-quality inventions, $c_2 > C_2^*(c_1, b)$ or for high-quality inventions, $c_2 \leq c_2^*(c_1, b)$, and the outcome is technology transfer for intermediate-quality inventions, $c_2^*(c_1, b) < c_2 \leq C_2^*(c_1, b)$. The two cost thresholds solve $\Gamma(b, c_2) = 0$ and are represented in Fig. 3. The higher cost threshold is increasing in the substitution parameter (representing less product differentiation), $\partial C_2^*(c_1, b)/\partial s \geq 0$. These cost thresholds generate two critical values for the R&D shock, $t(z, x_H^*) = c_2^*(b; s, c_1)$ and $t(z, x_L^*) = C_2^*(b; s, c_1)$, where $x_L^* < x_H^*$. Technology transfer occurs if the realization of the R&D shock is between these two values x_L^* and x_H^*.

5. Discussion

Tacit knowledge is an important asymmetry between the inventor and the adopter. Tacit knowledge is fundamentally different from adverse selection, moral hazard, and imperfect IP protections. This means that the economic effects of tacit knowledge differ from those commonly associated with these other types of frictions in the market for discoveries. This section considers some of the main differences between tacit knowledge and these other types of frictions. The discussion also suggests how the present model of tacit knowledge could be extended to include information asymmetries and limits on IP.

5.1. Adverse selection

Tacit knowledge differs fundamentally from asymmetric information problems in technology transfer. Information asymmetries due to hidden information can cause adverse selection problems in technology transfer (see Zeckhauser, 1996; Brocas and Carillo, 2007; Spulber, 2008, 2010a, 2010b, 2011b). However, the tacit knowledge problem considered here does not involve any type of strategic signaling or misrepresentation of information by the inventor. Tacit knowledge involves sufficiently complex know-how that may not lend itself to statistical inference. With tacit knowledge, the sender and the receiver must expend resources to transfer information and knowledge differences tend to persist. Also, in the present model, the receiver rather than the sender determines the quality of knowledge transmitted by investing in absorptive capacity.

The model of tacit knowledge differs from adverse selection models in which an economic agent with private information can "reveal" the information and often can communicate it without cost.[25] There are intrinsic limits on the inventor's capacity to transfer *know-how* and the adopter's capacity to absorb it. The model of tacit knowledge presented here could be extended to include adverse selection. In addition to tacit knowledge about how to apply the invention, the inventor also may have private information about the quality of the invention, c_2. Then, the existing firm would need to provide the inventor with information rents to induce revelation of the features of the technology. Lowe (2006) considers an agency model in which the licensee's probability of success depends on the inventor's effort and an exogenous tacit knowledge parameter. In contrast to Lowe (2006), the present model includes endogenous R&D rather than an exogenous invention.

5.2. Moral hazard

Tacit knowledge also differs from technology transfer under asymmetric information problems that are due to moral hazard (hidden action). The inventor's *know-how* places limits on the effectiveness of the inventor's efforts to transfer such knowledge, even if such efforts are observable. The present model could be extended to include moral hazard by having the inventor devote effort to transferring tacit knowledge to the existing firm. Then, the net benefits of own-use of tacit knowledge would also reflect the agency costs associated with providing incentives for effort to the inventor engaged in technology transfer.

Jensen and Thursby (2001) find that more than 70% of university inventions are sufficiently "embryonic" that after transferring the license to a firm, the inventor must provide additional effort to improve the probability of commercial success. Based on this observation, Jensen and Thursby (2001) present a principal-agent model of invention with moral hazard in which the licensee's probability of commercial success depends on the inventor's effort. The contract between the existing firm and the inventor provides the agent with incentives to devote effort to improving the existing firm's success rate in applying the invention. In Jensen and Thursby (2001), the licensee's probability of success depends on the inventor's effort and is assumed to be less than one so that technology transfer is necessarily imperfect; see also Macho-Stadler et al. (1996). In contrast to Jensen and Thursby (2001), the present model includes endogenous R&D rather than an exogenous invention.

5.3. Intellectual property

Tacit knowledge generates asymmetries in the allocation of knowledge that have different effects from a system of IP rights. It is well-known that concerns about revealing inventions discourage technology transfer and correspondingly favor own-use, just as do the costs of transferring tacit knowledge. Thus, imperfect IP protections would reinforce the results of the present analysis of the trade-off between own-use of inventions and technology transfer. The present analysis suggests that the effects of IP rights will differ across industries depending on systematic differences in inventors' tacit knowledge and the costs of codifying, communicating, and absorbing that knowledge. An empirical implication of the analysis is that variations in tacit knowledge across industries will affect the rate of technology transfer and the rate of entrepreneurship. Differences in technology transfer rates and entrepreneurship rates across

[25] Arora (1995) presents an adverse selection model with tacit knowledge and technology transfer in which adopters with greater value of know-how signal their type by greater first-period royalty payments, with second-period royalties providing incentives to technology transfer.

industries can provide indications of the effects of tacit knowledge. Mansfield (1994) finds that the importance of IP rights differs across industries and suggests that this may be due to differences in technological complexity.

The tacit knowledge model presented here suggests how the invention is distinct from the inventor's tacit knowledge. IP protections may be even more important for commercialization because the returns to transferring the invention must also cover the costs of codifying and communicating tacit knowledge.[26] According to the American Inventor's Protection Act of 1999 (35 U.S.C. 112), "The specification shall contain a written description of the invention, and of the manner and process of making and using it, in such full, clear, concise, and exact terms as to enable any person skilled in the art to which it pertains, or with which it is most nearly connected, to make and use the same, and shall set forth the best mode contemplated by the inventor of carrying out his invention."

The model of tacit knowledge presented here differs from economic analysis of R&D in which knowledge is a public good.[27] Consumption of tacit knowledge is rivalrous because of the scarcity of the inventor's time and effort. When knowledge is costly to codify, transmit, and understand and technology transfer requires significant interaction between the sender and the receiver, knowledge acquires some of the properties of private goods. The inherent nature of inventors' tacit knowledge may serve to limit some types of imitation and expropriation. The inventor can protect his IP by not codifying his knowledge or communicating it to others. However, patents and secrecy need not preclude others from independently acquiring tacit knowledge.[28]

6. Conclusion

Inventors often apply and develop tacit knowledge in the process of creating commercial, scientific, and technological inventions. Inventors' tacit knowledge, including their judgment, creativity, capabilities, and understanding of how the invention works, can make own-use of their inventions more productive than transferring the inventions to existing firms or specialized entrepreneurs. The inventor's tacit knowledge is important because it can overcome the competitive advantages in technology implementation that existing firms derive from complementary assets.

The problem of tacit knowledge therefore helps to explain creative destruction. The inventor becomes an innovative entrepreneur when the returns from own-use of inventions exceed the returns to technology transfer to existing firms or specialized entrepreneurs. The innovative entrepreneur embodies *both* tacit knowledge and the invention in the new firm. Tacit knowledge affects whether technological change occurs by transforming existing economic institutions or by establishing new ones. When tacit knowledge is significant, inventors with higher-quality inventions become innovative entrepreneurs and inventors with lower-quality discoveries transfer their inventions to existing firms. Efficient outcomes in the market for discoveries include inventors' own-use of tacit knowledge through innovative entrepreneurship.

Appendix A

Proof of Proposition 2. (i) Suppose that $z^*=z^E$, $b^*=0$, and $x^*=0$. Then, it follows that $\pi^E(t(z^E, x))\geq\pi^M(0, t(z^E, x))$ for all x so that $\Pi^E(t(z^E, 0))-K\geq\Pi^M(c_1)$. Because $t(z^E, 0)=1$, $\Pi^E(1)-K\geq\Pi^M(c_1)$. Conversely, let $\Pi^E(t(z^E, 0))-K\geq\Pi^M(c_1)$. This implies that $x^*=0$. To see why, suppose instead that $x^*>0$, which implies that $\pi^E(t(z^*, 0))<\pi^M(b^*, t(z^*, 0))$. From the inventor's objective function U in (18), it can be shown that $z^*\leq z^E$. From $z^*\leq z^E$ and Lemma 1, it follows that

$$\pi^E(t(z^*,0))-\pi^M(b^*,t(z^*,0))\leq\pi^E\left(t\left(z^E,0\right)\right)-\pi^M\left(b^*,t\left(z^E,0\right)\right).$$

Also, from $b^*\geq 0$, we have $\pi^M(b^*, t(z^E, 0))\geq\pi^M(0, t(z^E, 0))$ so that

$$\pi^E\left(t\left(z^E,0\right)\right)-\pi^M\left(b^*,t\left(z^E,0\right)\right)\leq\pi^E\left(t\left(z^E,0\right)\right)-\pi^M\left(0,\ t\left(z^E,0\right)\right).$$

But, $\pi^E(t(z^E, 0))-\pi^M(0, t(z^E, 0))=\Pi^E(t(z^E, 0))-K-\Pi^M(c_1)<0$, which is a contradiction. Therefore, $x^*=0$, which in turn implies that $z^*=z^E$ and $b^*=0$. (ii) From part (i), $\Pi^M(c_1)>\Pi^E(t(\theta^E, 0))-K$ implies that $x^*>0$. Then, $z^*\leq z^E$ and $b^*>0$. □

Proof of Proposition 3. Find the cross-partial derivatives and note that $U_{zb}(b, z)=V_{zb}(b, z)$, so that it is sufficient to consider only $U_{zb}(b, z)$. Substituting for $\partial x^*/\partial z$ and $\partial x^*/\partial b$ and rearranging terms, the expression for $U_{zb}(b, z)$ can be written as follows,

$$U_{zb}(b,z) = (1/2)\Big[\int_0^{x^*(b,z)}\pi_{bc}{}^M(b,t(z,x))t_x(z,x)\frac{t_z(z,x)}{t_x(z,x)}f(x)dx - \pi_b{}^M(b,t(z,x^*))\frac{t_z(z,x^*)}{t_x(z,x^*)}f(x^*)\Big].$$

If the product of the MRTS and the density function are constant in x for x in $[0, x^*]$, then $U_{zb}(b,z) = -(1/2)\frac{t_z(z,x*)}{t_x(z,x*)}f(x*)\pi_b{}^M(b,t(\theta,0))<0$. If the product of the MRTS of the knowledge production function and the density function are increasing in x for x in $[0, x^*]$, then $U_{zb}(b,\theta)<-(1/2)\frac{t_z(z,x*)}{t_x(z,x*)}f(x*)\pi_b{}^M(b,t(\theta,0))<0$. Therefore, $U_{zb}(b, z)<0$ for $f(x)$ well-behaved. □

Proof of Proposition 4. From Eq. (15) and the royalty function, we have

$$U(b,z) = \int_0^\infty R(b,c_2)dF(x) + (1/2)\int_{x^*(b,z)}^\infty \Gamma(b,c_2)dF(x)-kz. \tag{A1}$$

The marginal returns to R&D investment are

$$U_z(b,z) = \frac{\partial}{\partial z}\int_0^\infty R(b,c_2)dF(x) + (1/2)\int_{x^*(b,z)}^\infty \Gamma_c(b,c_2)t_z(z,x)dF(x)-k. \tag{A2}$$

Because the marginal net benefits of R&D investment for own-use of tacit knowledge by the innovative entrepreneur are positive for $x>x^*$, it follows that $U_z(b,z) > \frac{\partial}{\partial z}\int_0^\infty R(b,c_2)dF(x)-k$. This implies that the reaction function is greater than that with certain technology transfer, $z^*(b)>z^T(b)$, for any b. From Eq. (16),

$$V(b,z) = \int_0^\infty\left[\pi^M(b,c_2)-R(b,c_2)\right]dF(x)-\int_{x^*(b,z)}^\infty\left[\pi^M(b,c_2)-R(b,c_2)\right]dF(x)-hb. \tag{A3}$$

[26] Arora (1996) shows empirically that tacit knowledge can be bundled with patents so that stronger IP protections increase the efficiency of contracts that transfer know-how.

[27] In many economic models of R&D, knowledge is viewed as non-excludable because it diffuses easily and without costs. Arrow (1962, p. 171) argues that information is easy to steal because inventors must reveal knowledge to potential buyers, who then reproduce the knowledge "at little or no cost." As a consequence, inventors encounter difficulties in appropriating the returns from their information. Griliches (1957, 1992) and others view knowledge as an externality or "spillover" that not only diffuses freely but whose diffusion would be costly to contain, see also Cohen and Levinthal (1989). Stiglitz (1999, p. 310) argues that "Most knowledge is a global public good" diffusing without cost not only locally but around the world. Tacit knowledge, however, implies that diffusion of knowledge can be costly.

[28] http://www.uspto.gov/patents/index.jsp

The marginal returns to absorption investment are

$$V_b(b,z) = \frac{\partial}{\partial b}\int_0^\infty \left[\pi^M(b,c_2) - R(b,c_2)\right]dF(x) - (1/2)\int_{x^*(b,z)}^\infty \pi_b{}^M(b,c_2)dF(x) - h. \quad (A4)$$

Because π_b^M $(b,\ c_2) > 0$, it follows that $V_b(b,z) < \frac{\partial}{\partial b}\int_0^\infty [\pi^M(b,c_2) - R(b,c_2)]dF(x) - h$. This implies that the reaction function is less than that with certain technology transfer, $b^*(z) < b^T(z)$, for any z. With strategic complements (substitutes), the reaction functions are increasing (decreasing). Therefore, comparing the reaction functions when there is the option of entrepreneurship with the reaction functions when technology transfer is certain implies that $z^* > z^T$ and $b^* < b^T$, see Fig. 2. □

Proof of Proposition 5. Letting $Z = -z$, we can define the objective functions $u(b, Z) = U(b, -Z)$ and $v(b, Z) = V(b, -Z)$. The strategies Z and b take values in compact intervals on the real line $[-z^E, 0]$ and $[0, b^T]$ respectively. The objective functions $u(b, Z)$ and $v(b, Z)$ are twice continuously differentiable. The strategies Z and b are complements, $u_{Zb}(b, Z) = v_{Zb}(b, Z) > 0$ for all Z and b. Then, using Milgrom and Roberts (1990, Theorem 5), there exist smallest and largest pure Nash equilibria, (Z_L^*, b_L^*) and (Z_H^*, b_H^*), Letting $Z_L^* = -z_L^*$ and $Z_H^* = -z_H^*$, note that $z_L^* \geq z_H^*$ and $b_L^* \leq b_H^*$.

From the objective functions $u(b,Z)$ and $v(b,Z)$, we obtain $u_{Zk}(b,Z) = 1$ and $v_{bk}(b,Z) = 0$. Then, applying Milgrom and Roberts (1990, Theorem 6) implies the strategies (b, Z) at the smallest and the largest Nash equilibria are increasing in k. This implies that b_L^* and b_H^* are increasing in k and z_L^* and z_H^* are decreasing in k. Also, note that $u_{Zh}(b,Z) = 0$ and $v_{bh}(b,Z) = -1$. Then, b_L^* and b_H^* are decreasing in h and z_L^* and z_H^* are increasing in k. Recall that $\partial x^*/\partial z < 0$ and $\partial x^*/\partial b > 0$. These results further imply that

$$\frac{dx^*}{dk} = \frac{\partial x^*}{\partial z}\frac{\partial z^*}{\partial k} + \frac{\partial x^*}{\partial b}\frac{\partial b^*}{\partial k} > 0, \qquad \frac{dx^*}{dh} = \frac{\partial x^*}{\partial z}\frac{\partial z^*}{\partial h} + \frac{\partial x^*}{\partial b}\frac{\partial b^*}{\partial h} < 0.$$

The results on the probability of entrepreneurship follow because $1 - F(x^*)$ is decreasing in x^*. □

Proof of Proposition 6. Differentiate Eqs. (19) and (20) with respect to K,

$$U_{zK}(b,z) = -(1/2)\Gamma_c(b,c_2)t_z(z,x^*)f(x^*)\frac{\partial x^*(b,z)}{\partial K},$$
$$V_{bK}(b,z) = (1/2)\pi_b{}^M(b,c_2)f(x^*)\frac{\partial x^*(b,z)}{\partial K},$$

where $c_2 = t(z,\ x^*)$. Recall that $\partial x^*/\partial K > 0$, so that $U_{zK}(b,\ z) < 0$ and $V_{bK}(b,\ z) > 0$. Therefore, $u_{ZK}(b,\ Z) > 0$ and $v_{bK}(b,\ Z) > 0$. Using Milgrom and Roberts (1990, Theorem 6), this implies that b_L^* and b_H^* are increasing in K and z_L^* and z_H^* are decreasing in K. Recalling $\partial x^*/\partial z < 0$ and $\partial x^*/\partial b > 0$, this implies that

$$\frac{dx^*(b^*,z^*)}{dK} = \frac{\partial x^*(b^*,z^*)}{\partial K} + \frac{\partial x^*(b^*,z^*)}{\partial z}\frac{\partial z^*}{\partial K} + \frac{\partial x^*(b^*,z^*)}{\partial b}\frac{\partial b^*}{\partial K} > 0.$$

The set-up cost, K, decreases the entrepreneurship probability because $1 - F(x^*)$ is decreasing in x^*. □

Proof of Lemma 3. (i) By the envelope theorem, $\Pi^{L\prime}(c_2) = -D(p_2^L(c_1,\ c_2))$ and $\Pi^{M\prime}(c) = -D(p^M(c))$. Because of imperfect transmission of tacit knowledge, it follows that $c \geq c_2$, where the inequality is strict for some values of y. Therefore, $p^M(c) \geq p^M(c_2)$ so that $p^M(c_2) > p_2^L(c_1,\ c_2)$ implies that $p^M(c) > p_2^L(c_1,\ c_2)$. Because demand is downward sloping it follows that $D(p^M(c)) < D(p_2^L(c_1,\ c_2))$ and therefore $-\Pi^{M\prime}(c) \leq -\Pi^{\prime L}(c_2)$ and strictly greater for some values of y. This implies that

$$\Gamma_c(b,c_2) \leq \Pi^{L\prime}(c_2)\left[1 - \int_0^\infty a(b,y)dG(y)\right] < 0,$$

so that $t_z(z,\ x) < 0$ implies $\Gamma_c(b,\ c_2)t_z(z,\ x) > 0$. (ii) Because $-\Pi^{M\prime}(c) \leq -\Pi^{M\prime}(c_2)$, it follows that

$$\Gamma_c(b,c_2) \leq \frac{\partial(\Pi_1(c_1,c_2) + \Pi_2(c_1,c_2))}{\partial c_2} - \Pi^{M\prime}(c_2)\int_0^\infty a(b,y)dG(y)] < 0.$$

Therefore, $\frac{\partial\Gamma(b,c_2)}{\partial z} = \Gamma_c(b,c_2)t_z(z,x) > 0$. □

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