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Abstract: Innovative ideas have unique properties arising from low communication costs. But ideas come from knowledge that is costly to communicate. “Formalizing” knowledge—codifying, developing standards, etc.—reduces these costs. In a simple model, formalization is associated with changes in the nature of competition between two equilibrium regimes. In one, knowledge is formalized, new technology replaces old and patents increase innovation incentives. In the other, knowledge is not formalized, old technology coexists with new, patents decrease innovation incentives and firms sometimes freely exchange knowledge. The equilibrium changes as technology improves over a life-cycle, affecting firm strategy, innovation policy, geographic localization and more.

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I. Introduction

The economics literature typically describes R&D and investment in innovation as activities that create new knowledge. But some innovative activity is directed, instead, toward facilitating the communication of technical knowledge, sometimes to significant effect.

For example, as part of writing a general chemistry textbook during the 1860s, Mendeleev developed a periodic table to summarize experimentally-derived knowledge about chemical properties. This table facilitated the education of new chemists. Chemistry students no longer needed to study and absorb hundreds of seemingly unrelated experiments. Instead, they could readily infer chemical properties from the highly formalized representation in the periodic table. Along with new laboratory techniques for the analysis and synthesis of chemicals, this table changed the chemical industry, fostering some of the first industrial R&D laboratories, making innovation more geographically dispersed, and making firms more reliant on patents (Haber 1958, Moser 2007, 2010). This new representation of chemical knowledge changed the chemical industry because it changed the cost of communicating technical knowledge.

Other examples of such scientific abstraction include Newton's Laws and Maxwell's equations. In addition, other sorts of activities also "formalize" technical knowledge, thereby reducing communication costs. Observational or tacit knowledge is codified so that it can be referenced more easily—much technical industry literature consists of this sort of information. Technology standards play a similar role in reducing communication costs, especially where firms need to coordinate activity.

Similarly, "dominant designs" such as the Wintel standard reduce the complexity of knowledge, facilitating its spread. Finally, knowledge can be embodied in hardware or software so that it can be automatically applied. In each of these instances, an investment in formalization serves to reduce the marginal cost of communicating technical knowledge. Casual observation suggests that such formalizing activities account for an important part of industrial innovative investment. And the example of chemistry suggests that these changes in knowledge can exert a large influence on industry behavior and on firm knowledge strategies.

This activity of formalizing knowledge implies that communication costs are *endogenous*, that is, economic actors choose to invest in formalization depending on economic conditions. In contrast, the assumption in most of the literature is that communication costs are exogenously fixed. For example, exogenously low communication costs underpin Arrows's (1962) finding that innovations tend to be undersupplied in competitive markets because of insufficient appropriability and Romer's argument (1990) that innovations give rise to increasing returns to scale. Yet endogenous communication costs raise the possibility that these findings might be contingent on the market or technology and possibly subject to change over time.

The contribution of this paper is to explore a simple model where communication costs are endogenous. I revisit and generalize Arrow's 1962 model of innovation, which assumes zero communication costs. To this model I add a convex communication cost function, I allow fixed investments in formalization to reduce the marginal cost of communication, and I generalize the competition between firms using old and new technologies.

I find that the decision to formalize knowledge is associated with a variety of economic conditions, suggesting rich patterns of behavior beyond the standard models. The intuition that drives these results is simple: it does not pay to formalize knowledge unless the market is sufficiently large to recoup formalization costs. Conversely, producing a large output is typically too costly unless the technical knowledge has been formalized. This means that the decision to formalize is made jointly with decisions about output and pricing.

In particular, unformalized knowledge will tend to be associated with markets where the new technology coexists with the old. This is because when a new technology is not substantially better than the old—for example, during the early stages of a technology—then firms will not formalize the new knowledge and communication costs will act as a capacity constraint on the scale of the new technology. Then the new technology cannot feasibly replace all of the old, that is, innovation is not drastic. Of course, new and old technologies often coexist for sustained periods.[1]

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[1] Observers sometimes attribute this to product differentiation (e.g., Christensen 1997). Here, the technologies can coexist even when they are perfect substitutes. Technologies also coexist when they are embodied in durable capital goods.

This is important because I show that coexistence affects the behavior of new technology firms. In particular, if the old technology market is sufficiently competitive, then competition between new technology firms is "soft." New technology firms act strategically tough toward incumbent firms, but *softly* toward each other. For example, the entry of other new technology firms does not dissipate their rents, patents do not increase ex ante rents, and firms may be willing to freely exchange knowledge with each other in some circumstances. On the other hand, when innovation is drastic, competition between new technology firms is "hard," patents are needed to realize maximum rents and knowledge exchange occurs only under license or sale.

Thus behavior regarding technical knowledge can change dramatically depending on whether the market is in a "coexistence" equilibrium or a "drastic" equilibrium and this will vary systematically with characteristics of the market. With many industries, the quality of the new technology improves over time (e.g., see Rosenberg 1979). When this happens (and assuming that the old technology is competitive), the manner in which technical knowledge is acquired, protected, used to compete, exchanged, and diffused varies systematically with the maturity of the technology. That is, some technologies follow a sort of life cycle of technical knowledge. In the early stage (or in coexistence equilibria more generally), knowledge is communicated via costly personal instruction, making geographic localization, social networks, employee mobility and migration important and competition between new technology firms soft. In later stages (or in drastic equilibria generally), knowledge is formalized, teaching relies more on formal instruction, markets can more readily emerge for general human capital and the interactions between new technology firms are more strategic.

In this way, endogenous communication costs give rise to rich patterns of behavior that vary systematically with technological maturity and other market characteristics. This provides an explanation for several apparent paradoxes:

- why pioneer inventors in some technologies such as software often do not patent and often share knowledge, while large companies do most of the patenting in these technologies, even though large companies presumably have substantial complementary assets and thus might not need patents;

- why new communication and transportation technologies facilitate the global spread of technical knowledge needed for producing mature products, but early stage innovation often remains highly localized in places like Silicon Valley;
- and why developing nations that have grown by mastering mature technologies often experience a "middle income trap," facing difficulty innovating in new technology fields and hence find it difficult to move to the technology frontier.

These differences in behavior also have strong implications for policy. I show that while patents increase ex ante incentives to invest in R&D in the drastic equilibrium, patents actually decrease ex ante incentives in the coexistence equilibrium. This poses a significant difficulty for the design of a unified patent system. It appears that some features of the patent system treat early stage technologies appropriately, while others do not. Moreover, the free exchange of knowledge that can occur in the coexistence equilibrium is welfare improving, suggesting that policy regarding trade secrecy, employee non-compete agreements and immigration might all have important effects on early stage technologies.

Literature review

While the literature has touched on aspects of the costs of communicating technical knowledge, it has not identified the connection between formalization and market competition and the implications that follow. A large literature, of course, discusses information economics, but most of this concerns small quantities of information, such as an agent's private valuation. As such, this sort of information is not costly to communicate. In contrast, technical knowledge can require much greater "bandwidth" and, for this reason, can be costly to communicate.

Some scholars have observed that inventors can change the marginal cost of communicating technical knowledge, for instance, by codifying it (Nelson and Winter 1982, Cowan et al. 1997,1999, Foray 2004). This paper goes further, making the connection to market competition and drawing out implications that communication costs have for a variety of economic behavior.

The analysis in this paper concerns the communication of technical knowledge, meaning the detailed knowledge to design, build, install, operate and consume a technology and its products. In contrast much of the literature on innovation and economic growth focuses instead on "ideas," which are held to be non-rivalrous and non-excludable (see Romer 1990). As is well recognized, this analysis, however useful, abstracts away from some important practical realities such as communication costs. In this idealized depiction, ideas have zero communication costs. But in reality, what matters for production is *knowledge*, not individual ideas. The technical knowledge needed to produce something typically consists of very many ideas, not just a single idea. Moreover, some of these ideas might not codified or articulated; some might require a specific language or other background knowledge in order to interpret them ("absorptive capacity"); and users might need to understand not only the separate ideas, but also how they interact. Highly formalized knowledge will be, to a first approximation, non-rivalrous and not technically excludable, however, this is not necessarily true before knowledge has been formalized.

For example, Cohen and Levinthal (1989, 1990, 1994) argue that an important part of R&D spending is directed to building "absorptive capacity," the knowledge needed to interpret external knowledge and apply it to the firm's own technology.[2] Absorptive capacity is closely related to communication cost. To the extent that external knowledge is intentionally transferred, this spending is part of the communication cost. More generally, cumulative investments in absorptive capacity provide background knowledge that facilitates the communication of new knowledge.

Economic models often assume fixed communication costs or fixed costs of imitation (unintended communication), which are also often assumed to be small. My analysis complements these models, providing an endogenous interaction that leads to richer patterns of behavior. For example, Arrow's 1962 paper provides the starting point for both the normative theory of invention incentives (see Gallini and Scotchmer 2001 for a review) and for much of the descriptive theory of the role of innovation in industrial organization. Scholars, including Arrow (see 1969) have, of course, recognized that Arrow's assumption of negligible communication costs is not general and, for that reason, patents are not always "needed." However, my analysis suggests that the critical early phases of technologies will

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[2] Cohen and Levinthal discuss external knowledge from the public domain but they do not distinguish whether that knowledge was willingly shared or not nor do they explicitly consider external knowledge transactions between firms. Their analysis, in fact, applies broadly to all forms of external knowledge.

systematically tend to have substantial communication costs. The model in this paper extends the standard analysis to provide some consideration of innovation policy, both patent and otherwise, for this critical phase. Moreover, communication costs are significant not only because they provide a degree of appropriability, but they can also change the nature of innovative competition so that inventors might even share knowledge.

Indeed, economists have noted that inventors sometimes freely exchange knowledge, describing this as “extremely puzzling” (Allen 1983), “novel” (von Hippel 1987), and “startling” (Lerner and Tirole 2002; see also Harhoff et al. 2003, Henkel 2006, Schrader 1991 and Stein 2008). But knowledge sharing is only puzzling if one assumes that communication costs are negligible and that knowledge licensing is Pareto efficient. I show that when these conditions do not hold—as they might not during the early phase of a technology—then free knowledge exchange emerges naturally. More generally, MacLeod and Nuvolari (2009) review some of the historical literature and find many instances where nineteenth century inventors freely exchanged technical knowledge, including cases in important industries such as iron and steelmaking (Allen 1983, Meyer 2003), and steam engines (Nuvolari 2004).

A related issue concerns the difference between academic science and industrial research. Dasgupta and David (1994) highlight the different norms and incentives of these two systems. Aghion et al. (2008) see the two sectors providing different tradeoffs between creative control and research focus. My model complements these, suggesting that even within industry, research on early stage technologies might exhibit academic-like behavior, with sharing of knowledge and little reliance on patents. On the other hand, the formalization of knowledge required to publish scientific findings plays an entirely different role than formalization in industry.

My model generates patterns similar to those described in the product life cycle literature. Vernon (1966) hypothesizes that international production takes place only after knowledge to produce and market a new product is sufficiently standardized. This is an example of formalization as is the “dominant design” of Utterback and Abernathy (1975, Suárez and Utterback 1995, Utterback 1996). In other models, the patterns are similar but the causal mechanisms might be different such as with Christensen’s “disruptive innovation” (1997) and Meyer’s (2007) model of open source innovation that transitions into proprietary manufacturing. Generally, very little of the product life cycle literature pays much specific attention to the changing nature of the transmission of knowledge. In some formal models, such as those by Winter (1984), Klepper and Graddy (1990) and Klepper (1996), imitation figures prominently, but the ease of imitation is exogenously fixed. In contrast to all of these models, my model considers how the transmission of technical knowledge—both intended and imitative—might change with technological maturity. Because of this, my model provides empirical predictions that go beyond those of the product life cycle literature, affecting such features as geographic localization, patent propensity and human capital acquisition.

Eric von Hippel (1994, 2005) has highlighted the importance of communication costs for the nature of innovation. He shows that when technical knowledge is "sticky" (that is, difficult to communicate), users of the technology tend to do the innovation themselves rather than manufacturers. Similarly, Darby, Zucker and several co-authors find that the tacit knowledge of "star" scientists is often critical to the success of early stage firms.[3] These findings support the view that knowledge of early technologies is often unformalized.

Foray and Steinmueller (2003, Foray 2004) point out that codification of knowledge has an added benefit: new representations of knowledge sometimes facilitate the generation of new knowledge. For example, the periodic table not only reduced learning costs, but it also correctly predicted the existence of several new elements. In a similar vein, Mokyr (2002) ascribes a critical role to the generalization of practical knowledge during the Industrial Revolution. He argues that new "epistemic" knowledge created from such generalizations helped sustain innovation. In my model, new knowledge arises from the exchange of knowledge, but I do not consider the facilitating role formalization might have. While this latter role might be important, the mechanism that I highlight itself might also be critical to sustaining innovation, especially for early stage technologies when practical knowledge is not yet highly formalized.

Finally, the model here is related to one in Bessen and Maskin (2009). Innovative activity here is complementary and sequential, similar to that model. The early phase of the model here corresponds to

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[3] Successful entrants are located near the star scientists, active participation by the scientists is positively associated with a variety of firm performance measurements, close ties to scientists shortens the time to IPO and increases the IPO proceeds. See Darby and Zucker (2001), Darby et al. (2001), Zucker et al. (1998, 2001), Cockburn and Henderson (1998).

the conditions in that model that give rise to a particularly dynamic mode of innovation, so this model can be seen as providing an explanation for why those conditions might arise in practice.

In the next section I posit three assumptions about communication costs. Then, in the following two sections I describe a simple model and results. Section V contains four brief case studies illustrating the relevance of the model and Section VI concludes.

II. The Cost of Communicating Technical Knowledge

Technical knowledge

Consider the information or knowledge needed to build and use a technology. For the moment, ignore the distinction between knowledge and information. Let a technique, be a vector of *n* technical parameters, $\{t_1,t_2,..t_n\}$. Without loss of generality, the parameters can be binary, $t_i=(0,1)$. Let *S* be a vector representing the *m* monitored states of nature, also binary, $S=\{s_1,s_2,..s_m\}$.

A technology, *T*, maps each monitored state of nature to a technique, $T=T(S)$. A technology can thus be represented by $n\cdot m$ bits of data. This is the information measure of the technology, $I(T)\equiv n\cdot m$.

Cost of person-to-person teaching

Now, suppose that a single teacher wants to communicate technical knowledge to *L* students. I wish to assume generally that the cost of communication in this case is: 1.) proportional to the amount of information being communicated, *I*(*T*), and is 2.) convex in the number of students.

To motivate this assumption, it is helpful to compare teaching to Claude Shannon's model of a noisy communication channel.[4] The teacher initially broadcasts the information to her students and the duration (cost) of this broadcast will be equal to the amount of information divided by the communication rate. However, for a variety of reasons, the initial broadcast is received with errors. Errors might arise from the students' limited attention or cognition, or the imprecision of the teacher's language, or the difficulty of articulating the information. Students might lack the knowledge to

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[4] Arrow (1969) suggests this analogy.

assimilate and understand the information they receive, that is, they might lack sufficient "absorptive capacity" (Cohen and Levinthal 1989).

To correct these errors, each student's knowledge must be tested and the teacher will then re-transmit some portion of the information relevant to the detected errors. This process might then be repeated. Because this error correction cycle is unique to each student, the total time required for error correction increases with the number of students. Given limited resources for the teacher's time, for the classroom, equipment, etc., this means that each student generates a congestion externality.[5] Because of this, the average time (cost) of training a student increases with the number of students in the class, L. This assumption corresponds, of course, to the well-established empirical finding for school education that the effectiveness of education diminishes with class size. Of course, some economies of scale or network effects might work to reduce average costs with class size, but I assume that the combined effect is still one of increasing average cost.

This assumption can be written formally as

Assumption 1. Costs of teaching. The total cost of communicating the knowledge of technology T to L students is

$$c_u(L) = I(T)\, g(L)\, L, \qquad g(L), g'(L) > 0, \qquad g''(L) \geq 0.$$

The subscript "u" designates unformalized knowledge, in contrast to communicating formalized knowledge, designated with an "f".[6]

Formalized knowledge

It is possible to reduce the information measure of a technology through the use of formalized knowledge. For an example, consider typesetting systems where the typographer needs to know how to

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[5] In the simplest case, students sharing the same classroom must wait while the teacher corrects the knowledge of other students.

[6] Note that this formulation assumes a single quality of knowledge. In a more realistic model, the student might have more or fewer errors and hence more or less accurate knowledge, and additional teaching cost could communicate knowledge more accurately.

hyphenate words. In the most primitive form of knowledge, the typographer would need to learn the hyphenation points of all the words he is likely to encounter. This is a large instructional burden, but formalization of the knowledge of various sorts can reduce the learning cost:

1. Codification. Knowledge can be "expressed in a particular language and recorded on a particular medium" (Foray 2004, p. 74). This allows the knowledge to be communicated with less personal interaction. For example, the knowledge of hyphenation points can be codified by putting them in a dictionary. Then, in practical terms, the typographer need only learn the hyphenation points of the most frequently encountered words; the remaining words can be looked up in the dictionary as needed. This reduces the information measure of the technology from $I(T)$ to $I(T^*)$.
2. Standardization. By limiting the range of inputs, outputs and operating conditions, the number of states that need to be monitored can be decreased, thus decreasing the information measure of the technology as well. In the typesetting example, standardization on a single language reduces the information measure of the technology.
3. Modularization. By breaking the knowledge into semi-independent modules and using a division of labor, the amount of knowledge each worker learns is less. Examples of modularization include "innovation toolkits" (von Hippel and Katz 2002) and Application Programming Interfaces in software.
4. Abstraction. It is possible to derive general rules for hyphenating, for example, many words that end in "ing" can be hyphenated before that suffix. The typographer could be taught that rule (plus exceptions), thus further reducing the information measure. This can be called algorithmic knowledge, e.g., Donald Knuth developed a hyphenation algorithm. Abstraction is also a feature of scientific knowledge: science reduces observational data (e.g., hundreds of years of astronomical observation) to some simple relationships (e.g., Newton's laws of motion) that can be used to reproduce the observational data. This sort of abstraction also reduces the information needed to employ technologies. For example, the periodic table and associated techniques allowed complex craft methods of producing dyes to be replaced by chemical synthesis of a few well-controlled steps.

5. Embodiment/automation. The cost of communicating technical knowledge can also be reduced by embodying that knowledge in a physical form that acts on that knowledge.[7] For example, with computers, the hyphenation dictionary (or the algorithm) can be embodied in a computer program so that the typographer need not learn hyphenation. This also reduces the information measure of the knowledge needed to use typesetting technology. Of course, a wide variety of mechanical and electrical devices serve to embody technical knowledge as well as computer programs. When this embodied knowledge is used to allow a machine to perform work previously performed by humans, we call this automation.

There is, however, a fixed cost to formalizing knowledge. Let that cost be c_0. Generally, the cost of communicating formalized knowledge, designated by subscript "f" is as follows:

Assumption 2. Costs of communicating formalized knowledge. The total cost of communicating the knowledge of technology *T* to *L* students after that knowledge is formalized is

$$c_f(L) = c_0 + I(T^*)\, g(L)\, L, \qquad I(T^*) < I(T).$$

Here the average cost per student decreases in *L*, at least initially. If c_0 is large, then the variable portion of the cost might be trivial by comparison. The marginal cost of transmission for formalized knowledge is less than it is for unformalized knowledge, however, it is not necessarily zero, as is often assumed.[8]

Note that this perhaps ignores the greater difficulty of communicating more abstract knowledge compared to simple information. That is, with an algorithm, for instance, the ability of the student to understand depends more on the student's previous knowledge and experience. E.g., Newton's laws are not much help to recreate astronomical coordinates without knowledge of calculus. Of course, in reality,

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[7] With codification, the knowledge is stored in physical form. With automation, a device performs actions autonomously based on stored knowledge.

[8] In some cases, formalization might affect unit costs. For example, a typographer using a dictionary might take extra time to look up words. To keep things simple, I assume that if formalization increases unit costs, then this increase is included in the marginal communication cost.

technical knowledge is never pure information, but always relies on the user's previous experience and knowledge to be interpreted and translated into productive activity.

More generally, I have presented the distinction between formalized and unformalized knowledge in a highly stylized way. In a more realistic model, there would be degrees of formalization with a schedule of different fixed costs and different information measures. Nevertheless, this simple model helps identify some simple relationships between formalization and other economic variables. Also, while I assume that inventors choose to formalize based on relative costs, exogenous scientific developments can alter these costs.

Also, note that formalization not only affects the marginal cost of communicating technical knowledge; it might also affect the qualitative nature of that communication. Unformalized knowledge requires personal instruction and hands-on experience. The marginal cost of communicating formalized knowledge is less, but this communication might also permit less personal interchange, especially to the extent that abstraction and physical embodiment are involved. For example, more formalized knowledge might be communicated through trade journals, textbooks or scientific literature.

Appropriability

Finally, communication costs affect appropriability conditions in two ways. First, imitation costs must be at least as large as communication costs. That is, the cost of *undesired* communication cannot be less than the cost of *intended* communication. Knowledge holders can increase the cost of unintended communication, for example, by taking measures to keep the knowledge secret. Survey evidence suggests that these costs can be substantial (Mansfield et al. 1981, Levin et al. 1987). For this reason, high communication costs imply a high degree of excludability.

To capture this notion in a simple way, I assume that imitation costs are

$$C(L) = I(T)g(L)L + \mu, \qquad \mu>0$$

Comparing this to Assumptions 1 and 2 above, the first term represents the variable component of communication costs. This equals communication costs for unformalized knowledge; for formalized knowledge it equals communication costs less c_0. Described in this way, imitation costs are typically much less for formalized knowledge than for unformalized knowledge. Consequently, free-riding might be more of a problem for formalized knowledge, while unformalized knowledge might have significant excludability.

Second, the ability of patents to perform as efficient property rights also varies with formalization. This is because formalized knowledge is easier to describe and this characteristic is important for the clear delineation of the boundaries of property rights. Efficient operation of a patent rights system (or any property rights system) depends on predictable boundaries (Bessen and Meurer 2008). Unpredictability raises dispute risk and transaction costs. Indeed, several patent law doctrines (definiteness, enablement and written description requirements) can be interpreted as requirements that the patented knowledge is sufficiently formalized. And patent offices sometimes struggle to understand early stage technologies where the knowledge is often not highly formalized and therefore difficult for patent examiners to learn. All this suggests that transaction costs and dispute risks might be greater for unformalized knowledge.

III. Basic Model

The model is a generalization of Arrow's (1962) model of a cost-reducing innovation that is a perfect substitute for an existing technology. I assume that a worker can produce a single unit of output with the existing technology. Given total output, X, let price, p, be determined by $p(X)$, the continuous, twice differentiable inverse demand function, $p(X)>0,\ p'(X)<0$ with elasticity $\epsilon \equiv -p'(X)\,X\,/\,p<1$. To simplify the proofs, I assume that this elasticity is constant.

Suppose that there are N firms producing with the old technology and that there are M prospective inventors who can develop versions of the new technology. Only these M inventors have the accumulated knowledge and experience with the new technology to possibly bring it into production. If the ith prospective inventor invests R in R&D, that inventor can produce output with a version of the new technology that has quality or efficiency $q_i > 0$. I assume that the outcome of R&D is uncertain. In particular, the quality of technology, q_i, is determined as a random draw from continuous, differentiable cumulative distribution function $F(q)$, with lower support zero, unbounded upper support and finite mean. This distribution is common knowledge.

This technology quality represents the number of units of output that a single worker can produce so that firm output is $x_i = q_i L_i$ with trained labor L_i. If $q_i > 1$, the new technology requires less labor to produce a unit of output than the old technology and is thus cost-reducing. A more general model might allow the new technology to be differentiated from the old and, in general, product differentiation would soften competition. I wish to focus on a situation where the output of the new technology is a perfect substitute for the old output in order to highlight the effects of communication costs on softening competition.

I initially assume that inventors do not patent. Then the *i*th inventor's knowledge of her new technology can be transferred to others as follows:

1. Inventors can choose to exchange knowledge of their technologies with each other. Since the inventors already have deep knowledge of the technology by virtue of their investments, it should cost little for them to communicate the differences between their technologies to each other. I assume, without significant loss of generality, that knowledge exchange among inventors is costless. I initially assume that inventors efficiently exchange knowledge, coordinating on the most efficient technology with quality $q \geq max(q_1, q_2, ..., q_M)$. This allows for innovative complementarity, that is, by combining knowledge, inventors can derive a technique that is superior to any of their individual techniques.
2. The *i*th inventor trains L_i workers at a cost of $c_u(L_i)$ or $c_f(L_i)$, depending on whether the inventor chooses to formalize the knowledge or not. I assume that this knowledge is firm-specific, so that it is paid for by the employers and all workers, both in the old and new sector, receive wage w. It can be shown that the model generates the same results with general human capital (details available from author).
3. Third parties can copy the technology and train L workers at an imitation cost of $C(L)$. I will initially assume that imitation costs are so high that imitators never enter.

Below I will relax these initial assumptions and consider the role of patents, imitation, and knowledge transactions explicitly. Actions of the inventors and firms can be captured in a game with the following stages:

1. Each inventor chooses whether to spend *R* on research and development.
2. If the *i*th inventor invests, she draws technology with quality q_i, and these values are common knowledge.
3. Inventors can exchange technical knowledge by freely exchanging it or under licensing agreements. I initially assume that this exchange is costless and efficient, coordinating on the best available technology with quality q.
4. Each inventor chooses the number of workers to train and trains them. Imitators choose whether to enter and train workers also.
5. With output capacities determined by the numbers of trained workers, the firms, including the firms using the old technology, produce, set prices and sell.

I focus on groupwise symmetric Nash equilibria (symmetric among the *N* old firms and among the *M* new firms). Note that because I have modeled only a single period, there is no opportunity for strategic behavior around formalizing knowledge; the decision to formalize depends only on the least cost method of training the current workforce. Clearly a richer model might give rise to strategic investment in formalization and possibly a sort of standards competition.

IV. Basic Results

Formalization decision

For simplicity, I discuss results for the case where there are only two inventors, $M = 2$. The results can readily be expanded to the general case, but exposition is simpler with only two. I will index the two new technology firms as $i = 1,2$, and the old technology firms as $i = 3,...,N+2$ and, for ease of exposition, I treat *L* as a continuous variable. I look for subgame perfect Nash equilibria that are groupwise symmetric, solving by backward induction. In the last stage, prices are set given the numbers of workers trained in stage 4. If both new technology firms invest at stage 1, they simultaneously choose the number of workers to train in stage 4.

Consider the game when both new technology firms invest at the first stage. Then total output is $X = q(L_1 + L_2) + \sum_{i=3}^{N+2} L_i$ and firm profits for the new and old firms respectively are

(1a) $\pi_i = (qp(X) - w)L_i - c_j(L_i), \qquad i = 1{,}2 \quad j = u{,}f$

(1b) $\pi_i = (p(X) - w)L_i, \qquad i = 3,\ldots,N+2$

From this, assuming a group-wise symmetric equilibrium, the first order conditions for an interior solution are

(2a) $p(X) = \frac{w + c'_j(L^*)}{q(1-\epsilon s)}$ (2b) $p(X) = \frac{w}{1-\epsilon(1-2s)/N}$

where s is the share of total output produced by each new technology firm, L^* is the labor trained by each new technology firm and j is chosen as the least cost form of training.

First, consider the formalization decision as the number of workers per firm grows larger. Clearly, at very small values of L_i, unformalized knowledge will cost less because $c_u(0) = 0$ but $c_f(0) = c_0 > 0$. However, the marginal cost of unformalized training is always larger, so as L_i increases, at some point, L^f, formalized training will cost less. Furthermore, L^* increases with q, at least as long as N is sufficiently large (see Appendix). This means that a unique value of q corresponds to L^f. Call this value q^f. Then

Proposition 1. Formalization. As long as the optimal number of workers, L^*, for the new technology firms is small, specifically, as long as $L^* < L^f$, firms will not formalize knowledge. Similarly, if N is sufficiently large and $q < q^f$, then new technology firms will not formalize knowledge.

In simpler words, it does not pay to formalize unless the upfront cost of formalizing can be amortized over a sufficiently large number of workers. This is shown in Figure 1, which displays how training costs might vary with technology quality, q. The cost of unformalized training begins increasing from zero at the point where new technology firms can first profitably enter (discussed below). The cost of formalized training begins at a higher level, thanks to the fixed upfront cost, but then increases more slowly and is eventually overtaken at q^f.

Note that the competitiveness of the old technology market, as represented by the number of firms, N, can affect the formalization decision of the new technology firms. When a competitive market in the old technology coexists with the new technology, small changes in L^* do not affect the market price. Then increases in technology quality, q, increase $L*$. However, when there are only a few old technology firms, changes in q might decrease $L*$, depending on the elasticity of demand.

Coexistence

The nature of the equilibrium solutions depend on various parameters, most significantly technology quality, q. Different parameter values define different solution regions. I derive the threshold conditions for each region in the Appendix and just highlight the regions here.

First, unless the technology quality is sufficiently large, specifically unless $q > q^e$, where $q^e < 1$, new technology firms will not find it profitable to enter.

Second, if technology quality is even larger, specifically if $q > q^d$, where $q^d > 1$, innovation will be "drastic," that is, the old technology firms will drop out of the market because the new technology firms charge a price that is less than the unit cost of the old technology. This happens when the duopoly price is less than the wage, w. This region corresponds to Arrow's (1962) drastic innovation, except here it is for a duopoly instead of a monopoly.

The various regions from these two thresholds are also shown in Figure 1. Below q^e, new technology firms do not enter. As q increases above q^e but remains below q^d, the new technology firms enter and coexist with the old technology firms. At even better levels of technology quality, the old technology firms drop out. Note that these regions imply that formalization is loosely correlated with drastic innovation. At low levels of q, knowledge is unformalized *and* the technologies coexist; at sufficiently high levels of q, knowledge is formalized *and* innovation is drastic. In between there is a mixed area, but the existence of these two combinations is quite general, as we shall see below.

In some cases, there might also be a region where the new technology firms set a limit price. That is, the duopoly price might be larger than w, but the new technology firms nevertheless make out better by charging a price of w (or slightly less), driving the old technology firms out of the market. This limit price region occurs when $q > q^l$, where $q^l > 1$. Arrow (1962) called this behavior "nondrastic innovation," but in the context here it might be more accurately described as a limit priced region.

Putting these regions together, we get

Proposition 2. Coexistence. With N firms possessing the old technology and 2 firms possessing the new technology of quality q,

a. If $q^e < q < q^u \equiv min(q^d, q^l)$, where $q^e < 1 < q^u$, then a unique groupwise symmetric "coexistence" equilibrium exists where the old and new technologies are both used.

b. Firms will not formalize knowledge in some portion of this region. For N sufficiently large, old and new technologies will coexist and knowledge will by unformalized in the region $q^e < q < min(q^f, q^u)$.

c. For $q^u < q$, the old technology will no longer by used.

Thus, in general, a region will exist where old and new technologies coexist and where knowledge is unformalized. Note that new technology firms will enter even when the new technology is inferior to the old, in contrast to the common assumption that new, inferior technologies only appear when they address a differentiated market (e.g., Christensen 1997). Here, even without product differentiation, new technology firms can enter because the old technology firms charge an oligopoly price that exceeds cost. When the number of old technology firms grows sufficiently large, this possibility vanishes in the limit.

The generality of coexistence depends on the presence of positive communication costs. Specifically,

Proposition 3. If communication costs, c, are zero, then $\lim_{N \to \infty} q^e = q^u = 1$, so that the range of the coexistence equilibrium vanishes as N grows large.

The proof is in the Appendix, but this result follows from two simple intuitions. First, as just noted, as N grows large, new technology firms cannot enter until the new technology is at least as efficient as the old. Second, without communication costs, new technology firms can limit price as long as the new technology is more efficient than the old. On the other hand, when communication costs are positive and knowledge is not formalized, these costs act as a capacity constraint. If the capacity constraint binds sufficiently, then the new technology firms cannot limit price until their technology reaches quality q^l. That is, for less efficient technologies, they cannot scale up sufficiently to make limit pricing a profitable strategy.

The various solution regions are shown in Table 1 with some illustrative examples that I discuss below. Early on, new technology of weaving, dyeing and wireless communications coexisted with older technologies and relatively little knowledge was formalized. Before 1909 in aviation and before 1977 with ACE inhibiting blood pressure medications (Cockburn and Henderson 1994), innovators worked as researchers, without any commercial products or services. With mature technologies, knowledge was formalized and commercial activity took place at a large scale.

Because communication costs constrain capacity, they generate a non-null coexistence region even when the old technology market is highly competitive. Of course, in practice, other sorts of capacity constraints such as a limited supply of critical skilled labor sometimes play a similar role. Nevertheless, communication costs with unformalized knowledge are significant because they likely provide a rather general constraint on capacity for marginally advantageous new technologies, such as for early stage technologies.

The general existence of a coexistence equilibrium is important because it changes the nature of competition between firms using the *new technology*, including innovation incentives. To show this, I will focus here and in the remainder of the paper on the case where the number of old technology firms is large. There are, of course, important cases where the market for the old technology is not so competitive, however, it is difficult to obtain general analytical results for those cases.

From Proposition 2b there will generally be a coexistence equilibrium with unformalized knowledge. I contrast this competitive/unformalized equilibrium with a drastic equilibrium ($q > q^d$) with formalized knowledge, assuming that the market is sufficiently large to support formalization. Moreover, to keep things simple, I assume that for this drastic equilibrium the marginal cost of communication is so small that it can be ignored. This drastic/formalized case thus corresponds to the conditions often imposed in the literature. Clearly, not all industries and technologies fall into one of these two cases, however, as I discuss below, evidence suggests that they are both common enough and this stylized treatment highlights important differences in behavior.

In this regard, it is important to reiterate that I have modeled only one period and not an entire technological trajectory of sequential innovation. One can surmise that in a more general model, behavior would be shaped by expectations of future conditions. For example, if a large scale market is anticipated in the near future, firms might invest in formalizing knowledge even though that might be unprofitable at the current quality level of technology. That is, there might well be a transition region where firms behave as if they were in the drastic/formalized equilibrium. Nevertheless, even taking such considerations into account, many technologies go through decades of development before knowledge becomes highly formalized. Kitch's data (1977) show a mean delay of 29 years from first patentability of a technology to first commercialization; Gort and Klepper (1982) find a mean delay of another 29 years from first commercialization to the beginning of the "shakeout" phase. Thus even taking transition behavior into account, there is ample time for technologies to be in an unformalized/coexistence equilibrium for many years.

Old technology market and strategic interaction

In particular, new technology firms interact very differently in these two equilibria. Consider, for example, how each firm's technology influences the willingness of the other firm to exchange technology. Suppose, for the moment, that firms have not yet exchanged knowledge in stage 3. Let $\pi_i^*(q_i, q_{3-i})$ represent the equilibrium profit of the *i*th new technology firm at stage 2, before knowledge exchange.

Proposition 4. Strategic Interaction.

a. For the drastic equilibrium with zero marginal communication costs, $\frac{d\pi_1^*}{dq_1}, \frac{d\pi_2^*}{dq_2} > 0$ and $\frac{d\pi_1^*}{dq_2}, \frac{d\pi_2^*}{dq_1} < 0$.

b. For the coexistence equilibrium with unformalized knowledge,

$$\lim_{N\to\infty} \frac{d\pi_1^*}{dq_1}, \ \lim_{N\to\infty} \frac{d\pi_2^*}{dq_2} > 0 \ \text{ but } \lim_{N\to\infty} \frac{d\pi_1^*}{dq_2} = \lim_{N\to\infty} \frac{d\pi_2^*}{dq_1} = 0.$$

The proof is in the Appendix. As I develop below, this difference in behavior is at the root of differences in regard to the effect of patents and the free exchange of knowledge. In both equilibria, each new technology firm benefits from improvements to its own technology. However, each firm suffers from improvements to its rival's technology in the drastic equilibrium, but *not* in the competitive coexistence equilibrium. The drastic case corresponds to the standard intuition. Improvements to the rival technology increase the rival's market share and decrease the price in the drastic equilibrium. The rival becomes a tougher competitor with better technology.

However, in the competitive coexistence equilibrium, an improvement to the rival's technology will spur the rival to increase its market share, but, thanks to the competition from the old technology firms, the market price will not change. This means that each new technology firm will be unaffected by improvements to its rival's technology. The rival's increase in market share comes only at the expense of the old technology firms.

Thus three-way competition changes the nature of competition between new technology firms. Note that this result depends on a competitive market for the old technology. It might not obtain if, say, the market for the old technology were a monopoly. In that case, the market price would change, in general, affecting all firms. Thus this result puts a new twist on the Schumpeterian argument about the relative importance of competition and monopoly for innovation. Here, even when the incumbents do not innovate, technology competition differs depending on whether the incumbent market is a monopoly or is competitive.

Innovation incentives without patents

An inventor will choose to invest in stage 1 if the expected profits exceed the cost of innovation, *R*. The nature of the rents also differs between the coexistence/unformalized equilibrium and the drastic/formalized equilibrium. Substituting (2a) back into (1a), for interior solutions, the optimal rents equal

$$\pi^* = \frac{\epsilon s}{1-\epsilon s}\left(wL^* + c_j(L^*)\right) + \frac{\gamma c_j(L^*)}{1-\epsilon s}, \qquad \gamma \equiv \frac{d\ln(c_j/L)}{d\ln L} \tag{3}$$

where γ is the elasticity of the average teaching cost per student. The first term represents a markup over cost, $wL + c$. The second term can be interpreted as oligopsony rents earned on human capital. For the drastic/formalized equilibrium, γ equals zero, so the entire rent derives from the markup over cost, as in standard models. For the coexistence/unformalized equilibrium, on the other hand, profits come largely from rents on human capital. This is because s will generally be small in this region—market share, s, equals zero when q equals q^e, and it increases as q grows within this region. When market share is zero, the first term drops out.

The stage 1 investment decision with these rents can be compared to the social planner's second-best decision on whether to invest. It will be socially desirable to invest in stage 1 when the net change in social welfare exceeds innovation cost R. Consider the situation where the number of old technology firms, N, is asymptotically large. Then the pre-innovation price will equal the cost, w.

In the case of a drastic innovation, the new duopoly price will be less than w and the social planner will want to charge a lower price. As in the standard analysis, the net change in social welfare will consist of the additional consumer surplus from the drop in price, the duopoly profits of the new technology firms and a deadweight loss. In general, the profit of each firm will be less than the net social welfare and therefore the innovation incentive will be less than socially optimal. There will be some socially desirable innovations that are not profitable enough for inventors to invest.

On the other hand, when the innovation falls into the coexistence/unformalized range, the market price remains unchanged and the net social welfare is the cost savings realized by the new technology firms,

$$\Delta W = 2\int_0^{qL} (w - \frac{w}{q})\, dx - 2c_u(L) = 2\left((q-1)wL - c_u(L)\right)$$

leading to first order maximizing condition $(q-1)w - c_u'(L) = 0$. This is the same as first order condition (2a) when market share, s, is zero. Thus

Proposition 5. When knowledge exchange is Pareto efficient, when the number of old technology firms, N, is asymptotically large and when the market share of a new technology firm, s, is asymptotically small, private rents equal net social welfare in the coexistence equilibrium, generating socially optimal levels of investment in innovation.

In effect, private innovation incentives in the coexistence/unformalized equilibrium will be *approximately* socially optimal when the old technology market is competitive. The intuition behind this result is that rents do not dissipate to consumers in this setting and there is no deadweight loss because the market price remains unchanged. I have derived this result under the assumptions that knowledge exchange is Pareto efficient and that imitation costs are high; below I show that this result can hold even when these two assumptions are relaxed. Also, I have excluded dynamic considerations; the social planner might want a greater level of investment if formalization is expected to occur in the near future.

Innovation incentives with patents

For a similar reason to Proposition 5, patents do not significantly increase innovation incentives in the coexistence/unformalized equilibrium. The usual argument is that innovation incentives are larger in a monopoly than a duopoly because more rents dissipate to consumers in duopoly. Consider the effect of a broad patent that gives one new technology firm the power to exclude the other from the market. Assume that: 1.) each firm has a fifty percent chance of winning the patent ex ante (stage 1) as long as they both invest R, and 2.) that the patent holder and the other firm can agree to a patent license that earns joint profits equal to the monopoly rent. For the moment, I maintain the assumption that Pareto efficient knowledge exchange occurs in stage 3, allowing both firms to coordinate on the best technology with or without patents. In the drastic/formalized equilibrium, a straightforward calculation shows that the monopoly profit exceeds twice the duopoly rents. That is, the joint profit is greater with a broad patent. Since each firm has a a 50:50 change of winning the patent ex ante, its expected rents are half the monopoly rent, which is larger than the duopoly rent. Based on this standard reasoning, a broad patent will provide greater ex ante incentive to invest in innovation.

However, when the new technology is introduced into a competitive market, a firm with a broad patent on the new technology can exclude the other new technology firm, but not the old technology firms.[9] From Proposition 4, above, one firm's profit is unaffected by the other's technology in a competitive coexistence equilibrium. In this case, a patent does not increase joint profits. Even if the patentee hired the other inventor to train workers, the combined profits would not exceed twice the duopoly profit. Moreover, to the extent that patents impose costs on innovators—because of fees, legal

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[9] In general, the old technology would normally count as prior art so that a patent on the new technology could not read against the old.

costs, enforcement costs and litigation costs for defendants—joint profits will necessarily be *less* in the coexistence equilibrium under a patent regime. Hence,

> Proposition 6. Patents and incentives. Assuming efficient knowledge exchange, a broad patent increases ex ante innovation incentives in the drastic/formalized equilibrium, but not in the coexistence/unformalized equilibrium. To the extent that patents impose costs on innovators, ex ante incentives in the coexistence/unformalized equilibrium are strictly lower under a patent regime.

Note that patents are *privately* valuable in the coexistence equilibrium as long as patent costs are not too great. This is because the innovator with the superior technology can profitably license the patent in Stage 3.[10] However, because the innovators do not know ex ante who will have the superior technology, this ex post private value does not increase ex ante expected rents. Thus under these conditions, patents will be privately beneficial but socially welfare reducing.

Of course, I have assumed high imitation costs, C, so that free-riding is not an issue. However, this result holds even if this assumption is weakened, as long as the imitation cost still exceeds the cost of intentional learning for unformalized knowledge, $C(L) > c_u(L)$. This is because for small values of q, an imitator cannot profitably enter. Specifically, let q^i be the value of q that solves $\pi^*(q) = \mu$. At this value, an imitator makes zero profits; at smaller values, an imitator would make negative profits and so does not enter. Then the range of the coexistence/formalized equilibrium can simply be redefined as $q^e < q < min(q^f, q^u, q^i)$. In other words, even with imitation, a coexistence/formalized equilibrium still exists as long as imitation costs are positive. In this region, Propositions 5 and 6 hold. The effect of imitation is to possibly reduce the range of this equilibrium, but not to change behavior within the region. The actual extent of the coexistence region is, of course, an empirical matter. Free-riding remains a problem outside of this region, especially because imitation costs might be particularly low when knowledge is formalized.

These results also depend on the strong assumption that knowledge exchange is Pareto efficient. I relax this assumption in the next section. These results also do not consider dynamic behavior as

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[10] Technology can be licensed without patents, of course, but to the extent that patents facilitate profitable licensing, they will be privately valuable.

discussed above. In a dynamic model, patents likely increase innovation incentives during the transition period when formalization is expected in the near future.

Inefficient bargaining and free exchange

It often happens that innovations are complementary, meaning that if innovators exchange knowledge they can derive a new technique that is superior to both of their individual techniques. Suppose that by exchanging knowledge inventors can realize a superior technology of quality q such that $q > q_1 > q_2$. In this case, knowledge exchange is socially desirable. Without Pareto efficient exchange, innovation incentives will be socially insufficient because firm profits will generally be smaller if the firms do not have access to the best technology. Thus the assumption of Pareto efficient exchange is important for Propositions 5 and 6.

From Proposition 4, in the drastic/formalized equilibrium, firms will not necessarily want to exchange knowledge without compensation because this could reduce their profits. In this case, there is a knowledge externality. In the standard Coasean analysis, patents permit firms to transact over knowledge exchange for a license fee. This facilitates Pareto efficient exchange, “internalizing” the externality, as long as transaction costs are negligible. Thus patents might be important for increasing the returns to innovation in the drastic/formalized equilibrium not only by providing greater market power, but also by facilitating coordination on the best technology.

However, this logic does not apply in the coexistence/unformalized equilibrium. From Proposition 4 for the competitive equilibrium, $\pi_1^*(q,q) = \pi_2^*(q,q) > \pi_1^*(q_1,q_2) > \pi_2^*(q_2,q_1)$, so it is privately beneficial to both parties to freely exchange knowledge even if the innovative complementarity (q - q_1) is small. By comparison, for the drastic equilibrium this is generally not true and firm 1 will find free exchange beneficial only with a large innovative complementarity if at all. Thus

Proposition 7. Private returns to knowledge exchange. If the technology realized by exchanging knowledge has quality $q > q_1 > q_2$, then when a large number, N, of old technology firms compete and knowledge is unformalized, new technology firms privately benefit from exchanging knowledge even if $q - q_1$ is small.

This means that Pareto efficient exchange should take place in the coexistence/unformalized equilibrium (assuming that the old technology market is competitive) even without patents. With patent licensing, or with technology licensing negotiations more generally, bargaining might fail in the presence of transaction costs or asymmetric information. When this occurs in a competitive coexistence equilibrium, firms will still find it profitable to freely exchange information. Thus Propositions 5 should hold generally for the coexistence/unformalized equilibrium, with or without patents and with or without transaction costs. Similarly, as in Proposition 6, in the presence of transaction costs, patents will still be welfare-reducing in the coexistence/unformalized equilibrium.

Note that I am specifically discussing mutual exchange as opposed to unilateral sharing of knowledge. I assume that during exchange, each party can detect whether the other party is sharing knowledge and terminate the exchange if the other party fails to share. At worst, only partial knowledge will have been exchanged and incomplete knowledge might well be useless. Of course, if mutual exchange is beneficial in a repeated game, then inventors might be willing to unilaterally share knowledge, expecting reciprocal sharing in the future.

Nevertheless, this result goes against the conventional wisdom that free exchange of knowledge between inventors is surprising. That wisdom appears to depend on an assumption that a firm is harmed by improvements to a competitor's technology, but, as Proposition 4 shows, that assumption does not apply in all conditions. Free knowledge exchange occurs even when patents are available but when bargaining over a patent license (or sale) fails. This means that such bargaining failure does not necessarily reduce innovation incentives. Under these specific conditions of a competitive coexistence equilibrium with unformalized knowledge, there is no "anti-commons" (Heller and Eisenberg 1998). As I discuss below, these conditions seem to apply to some early stage technologies, but not to all technologies.

Thus patents play a very different role in a competitive coexistence equilibrium than in the drastic equilibrium and in much of the patent literature. In the competitive coexistence equilibrium with unformalized knowledge, patents do nothing to increase innovation incentives and optimal incentives are realized without patents. When patents are available in markets with these characteristics, bargaining failure might not be a problem, but unpredictable patent boundaries might be.

Finally, I have discussed knowledge exchange as a communication from one inventor to another, one firm to another. However, historically much knowledge has been exchanged by employees moving from one firm to another (Epstein 1998, Hilaire-Perez and Verna 2006, Jeremy 1981). Trade secrecy laws, laws providing strong enforcement of employee non-compete agreements, and other laws can prevent the free exchange of knowledge. Transactions can still take place—for example, an employee bound by a strong non-compete agreement could pay to be released from the employment contract (or their prospective new employer could). But to the extent that asymmetric information, transaction costs, etc. limit such transactions, knowledge exchange could be curtailed.

Other means of appropriation

Firms can often take private action to appropriate greater returns from innovation. Even without patents, new technology firms can merge, subject, perhaps, to antitrust regulations. Firms can also form patent pools or they can buy out others' patents—that is, they can build patent thickets—to create de facto broad patent coverage with greater market power.

However, technological maturity might affect the benefits of taking such actions. Because communication costs constrain the market for the new technology in the coexistence equilibrium, monopoly control of the new technology might not deliver any greater market power then, following from Proposition 4. On the other hand, if merging does not incur large transaction costs, then this might be advantageous in a drastic equilibrium. Similarly, in the drastic equilibrium, a firm can also benefit from buying its competitors' patents or amassing market power through a large number of overlapping patents generally. A firm establishing a dominant patent position in this way is said to build a patent "thicket." But note that the motivation to do so only exists during the drastic equilibrium when output is not constrained by communication costs. To the extent that the drastic equilibrium is associated with mature technologies, firms' propensity to patent should be larger with mature technologies, all else equal.

This might help explain the persistent relationship between early stage innovation and small entrepreneurs. While entrepreneurs without critical complementary assets might need patents or other strong appropriability to profit with mature technologies (Teece 1986), entrepreneurs lacking those assets, and perhaps even lacking patents, are not at a particular disadvantage during the early phase of a technology. However, to the extent that firms practicing the old technology have patents that read on the new technology, patents can serve to block entry to some degree.

Patent pools can serve a similar function to patent thickets if pooling serves to increase the joint market power of participants. But patent pools can also serve as a means to exchange knowledge, much like a licensing agreement (see Meyer 2003 on the Bessemer pool). While a licensing agreement facilitates exchange between two parties, a patent pool can facilitate exchange between multiple parties with complementary technologies. Many patent pools have, in fact, formed early in the life of a technology when rivals had blocking patents on complementary technologies (e.g., the sewing machine pool, see Lampe and Moser 2009).

V. Case Studies

A variety of casual evidence suggests the importance of formalization. Industry and technical trade publications, conferences and meetings regularly feature exchange of newly codified knowledge gleaned from working with new technologies and this has been a feature of industrial life at least since the nineteenth century (Nuvolari 2004, Mokyr 2002). Standardization of new products and processes is regularly part of the commercialization process, formal industry standards bodies play a critical role in many technologies such as the Internet, and many firms pursue “platform strategies” attempting to develop de facto standards. Much innovative activity is directed to embodying technical knowledge in hardware or software to automate it. For example, much information technology has embodied routine knowledge.

The core finding of the above model is that major instances of formalization of knowledge should be associated with changes in the scale of operations and business models, including how firms choose to protect and/or share knowledge. Several brief case studies are illustrative:

Synthetic dyes. The development of the periodic table, basic techniques of organic synthesis and an understanding of the structure of the benzene ring in the 1860s changed the nature of chemistry education and research, particularly for research on synthetic dyes. This formalization of knowledge permitted the expansion scientific chemical training, especially in Germany where the number of students in the chemistry labs of the universities and polytechnic schools grew rapidly to 20,000 by 1900 (Haber 1958, Bensaude-Vincent and Stengers 1996). This, in turn, facilitated the growth of large R&D labs in the German chemical industry and large scale research programs such as the thirty year research project to synthesize indigo. This change was also associated with a change in knowledge strategy. Moser (2007) documents that this transition was marked by a sharp increase in the share of chemical innovations that were patented. Figure 2A shows the sharp increase in the number of patents in force. Also, consistent with the notion that unformalized knowledge tends to be acquired by personal instruction, Moser finds that the change in chemical knowledge during the 1860s is associated with a greater geographic dispersion of chemical innovation.[11]

Digital mobile phones. The first widely used standard for digital mobile phones, GSM, was announced in 1987 and formalized in 1991. Other standards for digital cellphones emerged around that time (IS-54 in 1990 and IS-95 in 1995). The superior performance of digital phones on these standards facilitated rapid growth of the cellphone industry. These standards were also associated with a change in knowledge strategies of firms in the digital wireless communications industry. Beginning in 1962, firms used this technology for satellite communications. They primarily worked as contractors or consultants to the military and NASA. At that time, innovators freely exchanged knowledge. For example, Andrew Viterbi did not patent his decoding algorithm, used widely in cellphones today, choosing to share it instead.[12] Much key knowledge was published in academic papers. Beginning in the late 1980s, firms such as Qualcomm (which Viterbi co-founded) and Motorola, patented heavily and pursued aggressive

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[11] Some evidence suggests that this pattern might be more general. Teece (1977) documents that the cost of transferring mechanical technologies overseas by multinational firms decreases substantially with the age of the technology. Vernon (1966) cites evidence that firms do not export a technology until it has matured and is relatively standardized. Using patent citations as a proxy for knowledge spillovers, Jaffe et al. (1993) find that the localization of knowledge decreases with the age of a technology. Audretsch and Feldman (1996) find that early stage industries tend to be more highly localized and Desmet and Rossi-Hansberg (2009) find that older manufacturing technologies are less localized. Thus more mature technologies often seem to have lower communication costs and seem to diffuse more widely.

patent strategies (West 2008, Bekkers et al. 2002). For example, once the GSM standard-setting process was begun in 1987, participating companies raced to develop patents that would be included in the standard. Again, Figure 2 shows a sharp increase in patenting.

Heavier-than-air flight. Around 1908, after many decades of experimentation, a "dominant design" emerged for aircraft that identified the key design elements needed to make heavier-than-air flight feasible. This permitted the development of military aviation and later the commercial aviation market in the 1930s. The dominant design also lead to a sharp change in the knowledge strategies of innovators. Before, an international network of experimenters, including the Wright brothers, actively exchanged knowledge. Afterwards, some innovators, especially the Wright brothers, became secretive and began aggressive patenting (Meyer 2010).[13] This quickly lead to a situation of blocking patents, prompting the War Department to encourage creation of a patent pool.

The automatic loom. In 1895 the Draper Company introduced the Northrop automatic loom, which automated key tasks that had not been automated on previous power looms. This loom represented a greater degree of formalization both because it was a dominant design and because it reduced the amount of knowledge that a weaver needed to acquire.

Prior to this product, manufacturers produced power looms in a competitive market based on common technology. In 1814, Francis Cabot Lowell built the first commercially successful power loom in the US, followed three years later by William Gilmour. Both copied British designs, but both had to develop considerable knowledge anew — it took Gilmour over a year to complete his loom and even then he could not get it to work without the help of an experienced English weaver who knew how to operate the new machine (Bagnall 1893). Lowell patented his loom but Gilmour did not at first. Although Lowell's company sold patent licenses and sold some patented looms, only about 4% of their profits during the early years came from these activities, which they abandoned after a few years. Most of their profits came, instead, from their own production of cloth using the new technology (calculations available from the author). Gilmour, instead of patenting his design, freely shared it with other

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12. "If we had patented, it probably would have slowed down its acceptance, because no one patented in those days. AT&T and IBM patented for commercial reasons, but we were a small government contractor. (Viterbi 2008)

13. Others, such as Curtiss, patented, but also allowed other innovators to freely use their inventions (Shulman 2002).

mechanics. He and they went into the service business of custom building looms for manufacturers (Bagnall 1893). This behavior was not unusual: many mechanics of this time freely exchanged knowledge among members of their networks even when they obtained patents (Meyer 2006, Thomson 2009, Wallace 1978). Gilmour's design proved to be superior and was adopted by Lowell's company after a few years (Gibb 1950). This set the pattern for the loom building industry where textile manufacturers contracted for looms or developed the resources to build looms inhouse. Although many loom designs were freely exchanged, textile manufacturers nevertheless made persistently high profits for many decades because much of the unformalized knowledge of how to install, maintain and operate the new technology remained in short supply (Zevin 1971).

By 1895, this operational knowledge was much more formalized thanks to larger numbers of experienced personnel, the formation in 1865 of an industry trade association that published much practical knowledge, and the establishment of textile schools beginning in 1884. The Draper loom further formalized knowledge by automating key tasks, thus reducing the knowledge needed to be acquired by weavers. For this reason, the Draper loom quickly dominated sales to new mills in the U.S. South, which lacked an experienced textile workforce. At this time, the Draper Company engaged in an aggressive patent strategy, acquiring over 2,000 patents that covered a wide range of substitute technologies (Mass 1989). With this, they dominated the industry well into the twentieth century. A surge in patenting is seen in Figure 2, but note that this largely represents a change in patenting behavior, not an dramatic increase in innovation — there is a long record of important innovations before 1895 (Bessen 2011).

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While these case studies illustrate behavior consistent with the model, they are not necessarily representative of industry generally nor do they exhaust the patterns of behavior that are consistent with the model. Some technologies are inherently niche technologies because their applications are limited in scale. For example, steel minimills, which depend on limited supplies of recycled steel, operate as price-takers. Consistent with the model, they also engage in free exchange of know-how (von Hippel 1987, Schrader 1991). In other cases, the initial commercialization of some technologies occurs at sufficiently large scale to permit extensive formalization. For example, ACE inhibitor blood pressure medications went from a “pre-competitive” stage, where research was shared in academic publications, to a large-scale commercial phase, where knowledge was protected with patents (Cockburn and Henderson 1994). In effect, much of the technical knowledge required to use these new drugs safely and effectively was formalized during clinical trials. In other cases, innovators might not benefit from exchanging knowledge even in early stage technologies because there might not be significant complementarities. This seems to have been the case with the manufacture of gunpowder in the United States (Fisk 2009). On the other hand, Open Source licensing means that knowledge exchange continues for mature technologies such as Unix. Thus a rich variety of behavior appears to be consistent with the model, highlighting the importance of knowledge formalization.

VI. Conclusion

The simple notion that private parties can make investments that reduce the cost of communicating technical knowledge has a rich set of implications for economic behavior: it affects the nature of competition and human capital acquisition, the role of small firms, the use of patents and the free exchange of knowledge.

More generally, this analysis suggests that technological maturity might have importance for a variety of fields of study. For example, some scholars posit that technical knowledge defines the boundaries of the firm because some knowledge can be exchanged better within firms (e.g., Kogut and Zander 1992). Yet the returns to technical knowledge and the nature of knowledge exchange—and the effectiveness of extra-firm exchange, including licensing markets—changes with technological maturity, affecting mergers, make-or-buy decisions, the significance of entrepreneurs and more. Formalization might also affect the degree of decentralization within a firm.

Also, communication costs might help explain the apparent paradox that innovation with new technologies often appears to be highly localized despite dramatic improvements in telecommunications technology and the globalization of production. Close personal communication appears to be particularly important for unformalized early technologies, possibly explaining this pattern.

Similarly, the corresponding implication for economic growth is that it might be important to foster growth in *both* early and late phase industries. Nations that can foster the development of new technologies in both phases might be at a significant competitive advantage to nations that are specialized in mature technologies. This might explain the difficulty some nations have in moving out of a "middle income trap" (Gill and Kharas 2009).

Moreover, this analysis of communication costs poses a challenge for innovation policy. Most of the economic theory of innovation has assumed negligible communication cost and therefore it really only applies to mature technologies. This theory provides little practical policy guidance for early stage innovation. The patent system has the difficult task of handling not only very different types of technologies, but technologies at different stages of maturity all within a unified legal framework. Intuitions about patents that are true for mature technologies, might be detrimental for early technologies. For instance, some judges and legal scholars have argued that early stage technologies should have broad patent scope (Kitch 1977, Kieff 2001). But the analysis here suggests that this approach is ill-founded. More generally, other areas of policy such as trade secrecy law and the law regulating employee non-compete agreements might be arguably more important than patents for early stage technologies. A specific focus on policy for early stage technologies is important because without adequate incentives early on, the profitable mature stages might never be reached or perhaps reached only after a long delay.

Appendix

Proposition 1

The cost of unformalized training will equal the cost of formalized training when $L = L^f$, which solves $c_0 + I(T^*)g(L^f)L^f = I(T)g(L^f)L^f$. It is straightforward to show that this solves to a unique positive value. Also, taking the derivatives, $c'_u(L) > c'_f(L)$ for positive values of L. This means that when L exceeds L^f, formalized training will cost less and not otherwise. Thus inventors formalize knowledge when $L > L^f$ and not otherwise.

To complete the proof I will next show that the optimal value of L increase with q when N is asymptotically large. First, taking the limit of (2b) as N becomes infinite, $p = w$. This means that total output is X_0 such that $p(X_0) = w$. Each inventor's share of output is then $s = qL^* / X_0$. Also, plugging the price of w into (2a) and solving for s, yields

(A1) $$s = \frac{qL^*}{X_0} = \frac{q - 1 - c'(L^*)/w}{q\epsilon}$$

Treating L^* as a function of q, taking the derivative of both sides with respect to q, and solving for $\frac{dL^*}{dq}$ yields

(A2) $$\frac{dL^*}{dq}=\frac{(w+c')X_0-\epsilon q^2 w}{q(\epsilon q^2 w+X_0 c'')}.$$

Substituting from (2a)

(A3) $$\frac{dL^*}{dq}=\frac{p-\epsilon s(p+w)}{s(\epsilon q^2 w+X_0 c'')}>\frac{p(1-2\epsilon s)}{s(\epsilon q^2 w+X_0 c'')}>0$$

The first inequality because $p > w$, the second because $s\leq\frac{1}{2}$ and $\varepsilon < 1$. Because of (A3), L^* will increase with q until it reaches q^f which for which the equilibrium value of L equals L^f. Below this value knowledge will by unformalized, above it, formalized.

Propositions 2 and 3

First, consider the entry threshold for new technology firms. They can profitably enter when the equilibrium price exceeds their unit cost.[14] Since $c(0) = 0$, $c(L)$ is approximately zero for small L. Then the minimum unit cost for a new technology firm will simply be w/q. From (2b), entry at some scale will be feasible when

(A4) $$p=\frac{w}{1-\epsilon/N}>\frac{w}{q} \quad \text{or} \quad q>q^e\equiv 1-\frac{\epsilon}{N}.$$

Next, consider the condition for drastic innovation where the equilibrium price with N=0 is less than or equal to w. Setting the price equal to w in (2a) and rearranging, let

(A5) $$q^d\equiv\frac{1+c'(L^*)/w}{1-\epsilon/2}.$$

Also, by taking the implicit derivative of (2a) with N=0,

(A6) $$\frac{dL^*}{dq}=\frac{1-\epsilon}{q(\epsilon/L^*+c''/(w+c'))}>0.$$

This means that once the price falls below w, additional increases in q will increase total output (= $2qL^*$), driving the price even lower. From this it follows that the drastic equilibrium will hold in the region where
$q > q^d$.

Limit pricing will be feasible when the new technology firms can profitably supply the entire market at a price of w. For a given q, the new technology firms will need L_l workers each to supply the market where $p(2qL_l)=w$. It will be profitable for them to do so when

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[14] I maintain the assumption of efficient exchange of knowledge for simplicity. In a more realistic model, a firm might not share its knowledge under some conditions if that might keep the other firm from entering.

(A4) $(q-1)wL_l - c(L_l) > 0$ or $q > q^l \equiv 1 + \frac{c(L_l)}{wL_l}$.

Note by inspection that $q^e < 1 < q^d, q^l$. This shows parts (a) and (c) of Proposition 2. Part (b) follows directly from this and Proposition 1.

Finally, note from (A4) that $\lim_{N\to\infty} q^e = 1$. Also, $q^l = 1$ if $c = 0$. Proposition 3 follows from this.

Proposition 4

The first order maximizing conditions with no knowledge exchange are

(A5) $$p(X) = \frac{w + c'(x_1/q_1)}{q_1(1-\epsilon s_1)} = \frac{w + c'(x_2/q_2)}{q_2(1-\epsilon s_2)} = \frac{w}{1-\epsilon(1-s_1-s_2)/N}.$$

First, consider the drastic case, where $N = c' = 0$. Then these can be solved for equilibrium values

(A6) $s_1 = \frac{q_1 - (1-\epsilon)q_2}{\epsilon(q_1+q_2)}$ and $p(X^*) = \frac{w(q_1+q_2)}{(2-\epsilon)q_1q_2}$.

We seek to explore the variation of firm profits with the technology qualities of the two firms. Expressing profits of firm 1 as

(A7) $$\pi_1 = \pi_1(q_i, x_1^*(q_i), x_2^*(q_i)) = (p(x_1^*(q_i) + x_2^*(q_i)) - w/q_1)x_1^*(q_i),$$

we seek to investigate the sign of

(A8) $$\frac{d\pi_j}{dq_i} = \frac{\partial \pi_j}{\partial q_i} + \frac{\partial \pi_j}{\partial x_1}\frac{dx_1^*}{dq_i} + \frac{\partial \pi_j}{\partial x_2}\frac{dx_2^*}{dq_i}$$

where $i,j = 1,2$. I will show the calculation for i=2, j=1 and the reader can repeat the method for the other cases. Note first that by the envelope theorem, the second term is zero. Also the first term is zero. Then, using (A6),

(A9) $$\frac{d\pi_1}{dq_2} = q_1x_1p'\frac{d(1-s_1)X^*}{dq_2} = q_1x_1p'\left(\frac{(2-\epsilon)q_1X}{\epsilon(q_1+q_2)^2} - \frac{w(1-s_1)}{(2-\epsilon)q^2p'}\right) < 0.$$

The second part of the proposition concerns the case with positive communication costs (unformalized), but where N grows asymptotically large. The analog to (A6) is

(A10) $s_1 = \frac{(q_1-1)w - c'(x_1/q_1)}{\epsilon q_1 w}$ and $p(X^*) = w$.

For the case where i=2 and j=1, the first two terms in (A8) drop out as before, but now $\frac{\partial \pi_1}{\partial x_2} = 0$ because x_2 has no influence on the equilibrium price, thus

(A11) $$\frac{d\pi_1}{dq_2} = 0.$$

The other combinations follow in a similar manner.

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Table 1.

	Pre-commercial research $q < q^e$	Commercial, coexistence equilibrium $q^e < q < q^u, q^f$	Commercial, drastic equilibrium $q^u, q^f < q$
Unformalized knowledge	aviation < 1909 ACE inhibitors < 1977	power loom < 1840 dye chemistry < 1869 digital wireless < 1990 steel minimills	
Formalized knowledge			power loom > 1895 dye chemistry > 1869 digital wireless > 1990 ACE inhibitors > 1977

Figure 1. Solution regions

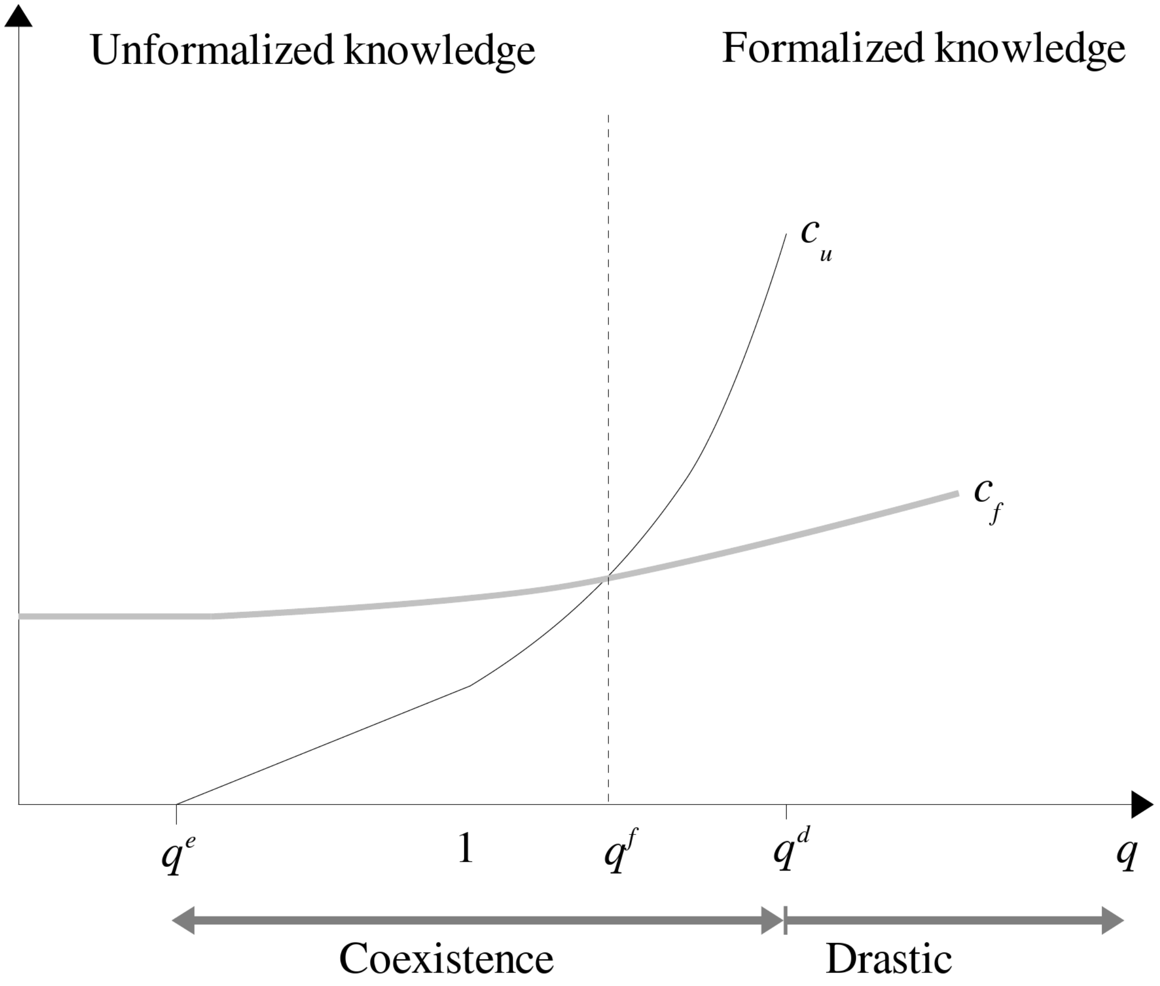

Figure 2. Changes in patenting with formalization