The Two Faces of Innovation

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Abstract: An important part of innovation is "formalizing" technical knowledge — reducing its marginal communication cost by codifying, developing standards, etc. In a model with endogenous communication costs, formalization only pays when technology is sufficiently developed. This changes the nature of competition. When new technology is substantially better than old, knowledge is formalized, new technology replaces old and patents increase innovation. But when new technology is not substantially better, it coexists with the old, patents can decrease innovation, and inventors sometimes freely exchange knowledge. Communication costs change as technology improves, affecting firm strategies, innovation policy, geographic localization, and standard-setting.

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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.

Consider some examples:

- **Periodic Table**. 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.
- **Wireless digital communication standards.** The first widely used standard for digital mobile phones, GSM, was announced in 1987 and finalized in 1991. By having key design elements in the standard, compatible cellphones were easier to design and build. Before the standard, much knowledge was freely shared, such as Viterbi's widely used decoding algorithm (Viterbi 2008, West 2008). Once the standard was announced, firms adopted aggressive patenting strategies, racing to acquire patents and have them included in standards (West 2008, Bekkers et al. 2002).
- **Heavier-than-air flight**. The first large public demonstrations of heavier-than-air flight took place in 1908. This was possible because key design elements had been identified, constituting a de facto standard.[1] Prior to this time, a robust international network of

tinkerers exchanged information about aircraft design and experiments (Meyer 2010). Once it became clear that flight was nearing commercial feasibility, these tinkerers, including the Wright brothers, largely switched from sharing knowledge to aggressive patenting. In fact, blocking patents delayed the development of the aircraft industry in the U.S. until the War Department instigated a patent pool in 1917.

- **Automatic loom.** In 1895, the Draper Company introduced the automatic loom, which mechanized key weaving tasks. Because this loom reduced the knowledge that weavers had to acquire, it became a de facto standard, especially for new mills in the South, which lacked an experienced textile workforce. Prior to then, textile equipment was competitively supplied (Gibb 1950). Since the early part of the nineteenth century, many important weaving innovations had been freely shared, including the most widely used power loom design (Bagnall 1893). But with its automatic loom, the Draper Company acquired a large number of patents, creating a patent thicket that enabled it to maintain a dominant market position for decades (Mass 1989).

These examples illustrate some different ways that knowledge can be formalized: by scientific abstraction, in a formal standard, in a de facto standard, or embodied in equipment. In each case, formalization served to reduce the marginal cost of communicating some part of the technical knowledge needed to implement and use the technology. Standardizing the knowledge, representing it in compact form and embodying it in hardware, made it easier to for large numbers of people to gain the knowledge they needed to build, install and operate the new technologies, thus facilitating widespread adoption.

Furthermore, these examples suggest that formalization of knowledge is sometimes associated with sharp changes in knowledge strategy. This can be seen in Figure 1 which charts the patents in force for technology classes related to these four examples. In each case, patenting increased

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1. These included the optimal shape for the wings, the design of an aeronautical propeller, the need for control along three axes, vertical rudder, tail, and the use of lightweight internal combustion engines.

dramatically around the time knowledge was formalized. Note that all of these technologies had substantial innovation prior to formalization, so these figures represent changes in strategy more than changes in innovation.

Formalization seems to be related to patterns of behavior not captured in standard models of innovation. Indeed, most of the literature assumes that the costs of communicating technical knowledge are exogenously fixed, usually near zero. 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. But in three of the above examples, industry participants took actions that substantially reduced the cost of communicating technical knowledge, implying that communication costs can be *endogenous*. Indeed, much of what is called "development" consists of such activities and many industry technical publications are filled with efforts to codify knowledge. The possibility of endogenous communication costs suggests that innovators might behave in ways not considered in the literature.

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.

Two general sorts of equilibria emerge from this model. In one, knowledge is formalized and the new technology drastically replaces the old. In this case, marginal communication costs are low and standard results about the undersupply of innovation, the benefits of patents, etc. apply. In the other major equilibrium, knowledge is not formalized and the new technology coexists with the old. Formalization is related to these different equilibria for a simple reason: 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. When the new technology market is not sufficiently profitable, firms will not formalize knowledge, communication costs will act as a capacity constraint on the scale of the new technology, and hence the new technology cannot feasibly replace all of the old. Of course, new and old technologies often coexist for sustained periods.

This is important because I show that coexistence affects the behavior of new technology firms. In particular, when the old technology market is competitive, 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.

These differences 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 difficulty for the design of a unified patent system. Also, 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. An innovation policy that achieves a balance between incentives for early and mature technologies is likely to involve much more than patent policy.

Literature review

While the economics 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. Similarly, 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.

A model of formalization also provides complementary insights to the literature on standards competition, such as the war between the Betamax and VHS standards for video recording (see Besen and Farrell 1994 for a review of this literature). Some papers argue that small initial advantages can be magnified into long term dominant market positions. One might expect, therefore, for industry participants to seek to establish standards as early as possible. But, in fact, this is often not the case. For example, video recording technology was around for 40 years before the Betamax standard was introduced in 1975. Video recorders for the consumer market were introduced beginning in 1963 and even Sony, the author of the Betamax standard, did not promulgate an interface standard then. The economics of formalization can explain this delay.

De facto standards, such as “dominant designs” feature prominently in the technology life cycle literature (Vernon 1966, Utterback and Abernathy 1975, Suárez and Utterback 1995, Utterback 1996). Many of the models in this literature highlight changes in firm entry (Gort and Klepper 1982, Winter 1984, Klepper and Graddy 1990, and Klepper 1996). According to these models, during the early stages of a technology, firms with relevant knowledge from outside the industry choose to enter. Later, when a dominant design is shared throughout the industry, mainly established firms in the industry develop new knowledge to improve the technology. Note that changes in the cost of transferring knowledge are implicit in the models. During the early stages, firms choose to enter presumably because they cannot efficiently transfer the technology via license or sale (see the discussion in Gort and Klepper, 1982). Later, however, essential knowledge is shared and firms compete on improving that shared knowledge. Formalization can explain these implicit changes and, moreover, explain rich patterns of behavior over the technology life cycle regarding patents, knowledge sharing and choice of geographic location.

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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.

Formalization is also relevant to the literature on patent pools (Lerner and Tirole 2004, Shapiro 2001). Pools are seen as a way to reduce the cost of licensing technology when a “thicket” of patents requires licenses from multiple patent holders. However, most modern patent pools are standard-setting organizations (SSOs). Because standard setting itself reflects a change in the nature of industry competition, these patent pools might play a different role. In fact, the evidence from some SSOs suggests that they might actually *promote* the creation patent thickets. For example, patenting rates soared after the creation of the first standards for 2G wireless as above.[3] While a full exploration of SSOs is beyond this paper, the model provides a first step for thinking about patent pools in a richer setting.

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

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3. Bekkers et al. (2002) find that about 90% of the essential patents in the GSM pool (GSM was one of the 2G standards) were filed after standards development started in 1982 and two thirds of the essential patents were filed after the SSO began deciding the exact implementation in 1987. Thus the GSM standard seems to have promoted a patent thicket rather than to simply have resolved a pre-existing one.

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.

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.[4] 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 the conditions in that model that give rise to a particularly dynamic mode of

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4. 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).

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 concludes.

II. The Cost of Communicating Technical Knowledge

Cost of person-to-person teaching

In order to implement a technology, it is necessary to train the people who will build it, install it, and use it. Suppose that a single teacher (say, the original inventor) wants to communicate technical knowledge to L students. This is the knowledge needed to build and use a technology. I assume that the cost of communication in this case is: 1.) proportional to the amount of knowledge being communicated, K, 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.[5] 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 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.[6] Because of this, the average time (cost) of training a student increases with the number

5. Arrow (1969) suggests this analogy.

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

$$c_u(L) = K\, g(L)\, L, \qquad g(L), g'(L) > 0, \qquad g''(L) \geq 0.$$

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

Formalized knowledge

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

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

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.
4. Abstraction. The periodic table is an example where scientific abstraction reduced the amount of information students had to learn (also Newton's laws and Maxwell's equations). Computer algorithms, such as Donald Knuth's algorithm for hyphenation perform a similar role.
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.

The effect of formalization is to reduce the amount of knowledge to be communicated from *K* to *K**. 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

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

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]

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

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, 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

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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.

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

$$C(L) = Kg(L)L + \mu, \qquad \mu>0$$

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.

Also, the ability of patents to perform as efficient property rights 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

My 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 *i*th 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 a continuous, differentiable cumulative distribution function, 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. The *i*th inventor can train 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).
2. 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.

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

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

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

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 2, 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 one or 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 2. 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 higher 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.

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 the examples from above. Early on, new technology of weaving, dyeing and wireless communications coexisted with older technologies and relatively little knowledge was formalized. Before 1908 in aviation, 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 in the remainder of the paper on the case where the number of old technology firms is large. I do this because it is easier to obtain general analytical results for this case. I will contrast the coexistence/ 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 the marginal cost of communicating formalized knowledge is negligible. 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, but the examples above suggest that they are not uncommon.

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

Importantly, 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

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

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 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

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.

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 will reduce social welfare.

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/ unformalized equilibrium can simply be redefined as $q^e < q < min(q^f, q^u, q^i)$. In other words, even with imitation, a coexistence/ unformalized 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.

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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.

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, there is no "anti-commons" (Heller and Eisenberg 1998).

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 near-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. 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 the 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, as illustrated in Figure 1.

This might also 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. 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.

This also has strong implications for policy. While most models of innovation assume low imitation costs, scholars recognize that this assumption is not general and, for that reason, patents are not always needed. However, my analysis suggests that the critical early phases of technologies will *systematically* tend to have substantial communication costs and patents can actually decrease ex ante incentives then. This poses a difficulty for designing a patent system that can handle both early and mature technologies. Some features of the patent system work to restrict patenting to formalized technologies, in line with this analysis. For example, the enablement doctrine requires that a patent provide the formalized knowledge needed to reproduce the invention. In practice, however, the enablement doctrine is often not enforced rigorously. On the other hand, other doctrines work to encourage early stage patenting, such as the informal doctrine held by some judges that “pioneer patents” should be given broad scope, a view supported by legal scholars Kitch (1977) and Kieff (2001).

More generally, 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;
- why 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;[11]

Of course, this is a highly stylized treatment of knowledge formalization. I have not considered the role of universities in formalizing knowledge, nor the differences between proprietary and open standards, nor strategic behavior around transitions from one equilibrium to another. Nevertheless, to the extent that formalizing knowledge appears to constitute a large part of innovative activity, consideration of endogenous communication costs is important.

Appendix

Proposition 1

The cost of unformalized training will equal the cost of formalized training when $L = L^f$, which solves $c_0 + K^* g(L^f)L^f = Kg(L^f)L^f$. It is straightforward to show that this solves to a unique

11. 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.

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.[12] 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,

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12. 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.

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

This means that once the price falls below w, additional increases in q will increase total output (= 2 $q\,L^*$), 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

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

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

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

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

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

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) $$\frac{d\pi_1}{dq_2} = q_1 x_1 p' \frac{d(1-s_1)X^*}{dq_2} = q_1 x_1 p' \left(\frac{(2-\epsilon)q_1 X}{\epsilon(q_1+q_2)^2} - \frac{w(1-s_1)}{(2-\epsilon)q^2 p'} \right) < 0.$$

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

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 < 1908	power loom < 1840 dye chemistry < 1869 digital wireless < 1990	
Formalized knowledge			power loom > 1895 dye chemistry > 1869 digital wireless > 1990

Figure 1. Changes in patenting with formalization

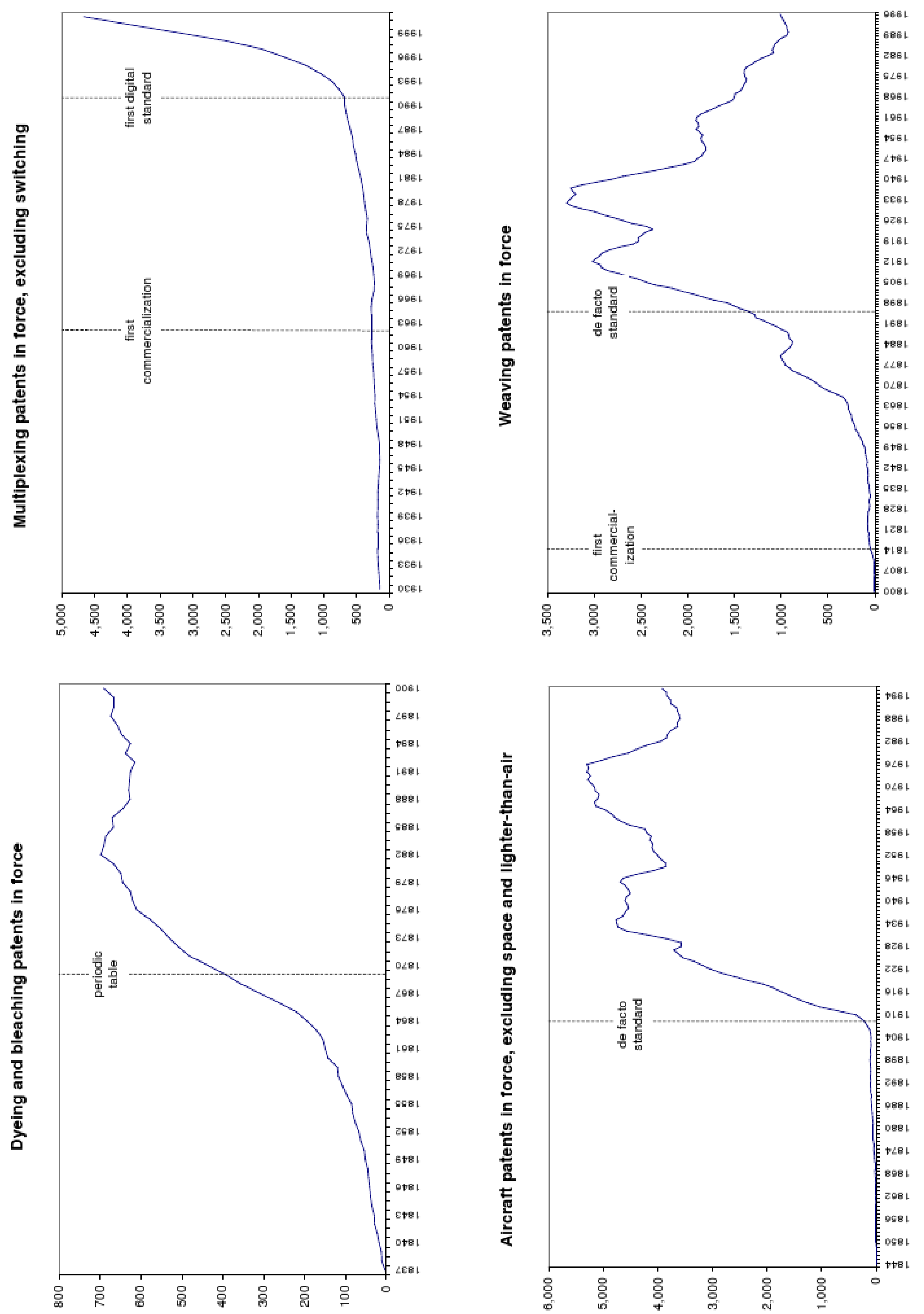

Figure 2. Solution regions