COMMUNICATING TECHNICAL KNOWLEDGE

Boston University School of Law Working Paper No. 10-35
(October 27, 2010)

James Bessen

Communicating Technical Knowledge

by James Bessen
(Boston University School of Law)

version: 10/2010

Abstract: In patent theory, the cost of communicating technical knowledge is small. In human capital theory, it is large. But evidence suggests that these costs are actually endogenous. Firms invest in reducing communication costs, but only when technology is sufficiently advanced. This can make competition different for early stage technologies: patents do not increase innovation incentives, employee mobility matters and inventors might choose to freely exchange knowledge. Behavior and optimal policy differ then. Endogenous communication costs help explain changes in patent propensity, in the geographic localization of innovation and why successful developing countries have difficulty moving to the innovation frontier.

JEL Codes: O3, D83, L1

Keywords: technology, knowledge, diffusion, spillovers, human capital, information good

jbessen@bu.edu

Previously titled "The Two Faces of Technical Knowledge." Thanks to helpful comments from Philippe Aghion, Wes Cohen, Dominique Foray, Philippe Käser, David K. Levine, Mike Meurer, Eric von Hippel and participants at workshops and conferences at Ascona Switzerland, BU, the NBER, and Paris.

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 thousands 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 less reliant on trade secrecy and more reliant on patents (Haber 1958, Moser 2008, 2009). 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. Also, technical standards and "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 a good deal of industrial innovative investment.

The communication of technical knowledge is essential for the application of that knowledge in production, for the improvement of that knowledge and for the development of new knowledge. As such, the knowledge involved is often complex and not necessarily well-articulated. Broadly conceived, the cost of communicating this technical knowledge can include the cost of extensive interaction between teacher and student and extensive experimentation to verify the student's acquisition of the knowledge, possibly even re-creating it. Because technical knowledge is often not highly formalized, these communication costs can be much greater than the mere cost of transmitting information.

Moreover, the activity of formalizing knowledge suggests 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. While the communication costs of human capital are typically assumed to be high, the communication costs of inventions and technical knowledge are usually assumed to be low. For example, 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]

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 the 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. This is important because many technologies improve gradually over time (e.g., see Rosenberg 1979). Often new technologies are initially inferior to the old technology but eventually become substantially better. 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.

---

1. Observers sometimes attribute this to product differentiation (e.g., Christensen 1997). Here, the technologies can coexist even when they are perfect substitutes.

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. This life cycle for technical knowledge is not necessarily identical to some of the technology life cycles discussed in the literature, which often focus on firm entry rates rather than on the use of knowledge. Nevertheless, evidence I discuss below suggests that coexistence equilibria might be common during the early stages of many technologies and possibly in other circumstances as well.

Thus endogenous communication costs give rise to rich patterns of behavior that vary systematically with technological maturity and other market characteristics. This means that the conventional wisdom about patents and knowledge sharing might apply in some circumstances (e.g., drastic equilibria), but not others; to some phases of technology (mature), but not all. This has important implications for several policy areas including patents, trade secrecy and employee mobility.

Endogenous communication costs might also explain 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 moving to the technology frontier.

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 rich 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.

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). 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 *systematically* tend to have substantial communication costs. The model in this

---

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.

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.

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, 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. This finding is closely related to my result that production tends to be small scale when communication costs are high.

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 innovation, so this model can be seen as providing an explanation for why those conditions might arise in practice.

Ideas or knowledge?

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 sharply distinguished from human capital (see Romer 1990 or Jones 2005). Ideas, it is held, are inherently non-rivalrous and not excludable except to the extent that patents limit use. An idea can be replicated at zero cost, giving rise to increasing returns in production (Romer 1990). However, because intellectual property protection is imperfect, an idea can "spillover" to competitors, creating a free-riding externality. Because of this, private rents are less than the social value of the idea, so ideas will tend to be under-supplied in a competitive market (Arrow 1962).

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. For example, the source code of a software program that instructs a computer how to add is a nonrival "idea" that can be copied at low cost. But to actually perform addition with such a program requires the knowledge of how to compile that code in its given language, to install the executable, to operate the computer, etc. 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. In general, production that involves humans requires a combination of human capital and ideas. Moreover, because the ideas cannot be used without additional human knowledge, this knowledge is typically a perfect complement to the ideas. That is, ideas are economically worthless without the necessary associated knowledge. As Boldrin and Levine note (2008, Chapter 7), economic value resides in the usable copy of the idea, not in the abstract idea itself.

Of course, where that knowledge is readily available at low cost, then the abstract model of ideas is a useful approximation to reality. For instance, this might be true where technical knowledge is highly formalized and supplied in competitive markets as general human capital. However, such circumstances are not general and the difference is important for several reasons.

First, although ideas might be copied at low cost, this does not mean that knowledge has low excludability without patents. If prospective users can be excluded from using the knowledge needed to put an idea into production, then they can be excluded from using the ideas as well. To cite an extreme example, alchemists, including Isaac Newton, often wrote their ideas in secret codes. While their manuscripts could be copied at low cost, the *use* of this knowledge was limited to those exclusive few who knew the code. Everyone else had high imitation costs.

Below I argue that communication costs are related to the costs of imitation and hence to excludability. Because of this, unformalized knowledge can have sufficient appropriability even without patents. Then, instead of knowledge "leaking out" in the form of spillovers, knowledge is exchanged—it is licensed or sold; or it is freely exchanged; or exchange happens indirectly through employee mobility.[3] When this is true, inventors might consider the benefit of their knowledge to other parties when making investment decisions, thereby internalizing knowledge externalities.

The distinction between knowledge and ideas is also important for the nature of competition. When firms have accumulated different background knowledge, they have different "absorptive capacities" to use a new technology (Cohen and Levinthal 1990, 1994). Firms that have not accumulated the necessary background knowledge of a new technology cannot readily use it. This means that different groups of firms use different technologies so that competition is between technologies (as in the standards and network effects literatures) as well as between firms using a particular technology. In this case, an individual innovation is relevant only to firms using a particular technology, a richer environment than that depicted in, say, the patent race literature. Where an earlier literature looked at the persistence of monopoly with regard to an individual innovation, here I obtain results about how monopoly or competition in an incumbent technology affects competition among firms using a new technology.

---

3. Unfortunately, the term "spillover" is sometimes used to include any kind of information sharing, not just unintended leakage of knowledge. I use the more limited sense here.

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 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

4. Arrow (1969) suggests this analogy.

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 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:

---

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.

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, technical knowledge is never pure information, but always

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.

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 and unbounded upper support. This distribution is common knowledge.

This technology quality represents the number of units of output that a single worker can produce so that 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.
2. If the ith 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) $p(X) = \dfrac{w + c_j'(L^*)}{q(1-\epsilon s)}$ (2b) $p(X) = \dfrac{w}{1 - \epsilon(1-2s)/N}$

where s is the share of 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.

Thus 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.

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 do not exchange knowledge in stage 3. Let $\pi_i^*(q_i, q_{3-i})$ represent the equilibrium profit of the *i*th 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

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

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

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 additional consumer surplus from the drop in price, 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.

For a similar reason, 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 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. 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.

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

---

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.

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.

Inefficient bargaining and free exchange

Suppose that by exchanging knowledge inventors can realize a superior technology of quality q such that $q > q_1 > q_2$. That is, the inventors possess complementary knowledge and knowledge exchange is socially desirable. Without Pareto efficient exchange, innovation incentives will be 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, $\pi_1^\ddagger(q,q) = \pi_2^\ddagger(q,q) > \pi_1^\ddagger(q_1,q_2) > \pi_2^\ddagger(q_2,q_1)$, 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 and 6 should hold generally for the coexistence/ unformalized equilibrium, with or without patents and with or without transaction costs.

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). As I discuss below, these conditions seem to apply to some early stage technologies, but not to all technologies. Much of the evidence advanced regarding anti-commons (e.g., Murray and Stern 2007, Williams 2010) relates to biotechnology, which might well be different.[10] Moreover, even where free knowledge exchange does take place, it is not clear that the effect of patents on early stage technologies is always benign. As I noted above, patent boundaries might be much less predictable when knowledge of the technology is highly unformalized. This could give rise to disputes that reduce innovation incentives (Bessen 2009, Bessen and Meurer 2008).

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.

---

10. Perhaps for these innovations the old technology markets (often small-molecule pharmaceuticals) are not highly competitive or the innovations are drastic.

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 (see Cockburn and MacGarvie 2010).

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. Empirical Relevance

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 (Autor et al. 2003).

Also, the model implies that the maturity of a technology should affect communication costs and that these should in turn affect other industry characteristics under certain conditions. That is, the model predicts that behavior will change as a technology matures when new technology does not at first completely replace an older technology that is competitively supplied. These conditions apply in many industries where innovation is highly incremental such as in information technology. These conditions might not apply everywhere. For instance, in biotechnology innovations are sometimes drastic, such as methods using recombinant DNA to produce erythropoietin.

Nevertheless a variety of evidence suggests that behavior in many industries changes with technological maturity in ways that are consistent with the model. Although these phenomena might have other explanations, the apparent importance of technological maturity as an explanatory variable suggests the empirical relevance of this analysis:

1. The nature of training and technology diffusion changes as technologies mature.

Historians describe how the early mechanics of the Industrial Revolution typically learned their skills and knowledge through close personal exchange (Meyer 2006, Wallace 1978, Thomson 2009, Rosenberg 1970). Social networks were important and the relationships between teachers and students were sometimes supplemented with family relationships. Because of the importance of personal interchange, inventive activity was highly concentrated in a small number of regions. And the international diffusion of technology depended heavily on the migration of mechanics knowledgeable of the newest techniques (Jeremy 1981). By the end of the nineteenth century, both the products and the training of workers were much more standardized and new technology spread rapidly over the globe.

Some evidence suggests that this pattern might apply today as well. Teece (1977) documents that the cost of transferring mechanical technologies overseas by multinational firms decreases substantially with the age of the technology.[11] Vernon (1966) cites evidence that firms do not export a technology until it has matured and is relatively standardized. Moser (2009) finds that the formalization in chemical technology associated with the periodic table decreased the localization of the chemical industry. 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. 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.

Conversely, developing nations that have realized economic growth thanks to the export of mature technologies from advanced nations sometimes find it difficult to master policies that foster the early stage innovation needed to move to the innovation frontier. Development economists (Gill and Kharas 2007, 2009) have identified a common pattern of a "middle income trap" that could be explained by differences in knowledge acquisition.

Other aspects of human capital acquisition seem to change with technological maturity as well. Bartel and Lichtenberg (1987) find that the demand for educated workers declines with the age of the technology employed. This makes sense if schooling complements the ability of workers to learn unformalized knowledge.

---

11. For chemical and petroleum refining plants, he finds that the age relationship is weaker, but the cost decreases with the novelty of the technology.

2. Startups rely on hard-to-transfer knowledge

Darby, Zucker and several co-authors have studied the relationship between "star" scientists in biotechnology and the development of successful startup businesses based on new biotechnology. They find that active involvement by the star scientists (who work mainly at universities) is critical to commercial success.[12] More generally, other studies show that participation of university scientists is essential for successful commercial licensing of their discoveries and this participation increases university royalties.[13] All of this suggests that critical knowledge is not highly fungible with these early phase technologies.

For similar reasons, some researchers have argued that the startups of Silicon Valley benefit from high employee mobility encouraged by California's lax enforcement of employee non-compete agreements (Gilson 1999, Hyde 2003).

3. Entry by new firms does not eliminate rents during the early phase.

Studying one of the first major new industrial technologies in the US, Zevin (1971) found that profits persisted for nearly three decades in the textile industry despite high levels of firm entry and widely available equipment. He attributes this to the limited supply of individuals who had the skills and knowledge to build, install, operate, manage and maintain the new technology.

This pattern seems more general. In received theory, firm entry dissipates rents and thereby reduces innovation incentives. However, Gort and Klepper (1982) find the opposite in a study of 46 product life cycles: innovation rates were greatest during the early phases of the technology when firm entry was greatest, consistent with the model.

---

12. 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).

13. Jensen and Thursby (2001), Colyvas et al. (2002), Agrawal (2006), Agrawal and Henderson (2002), Lach and Schankerman (2003).

4. Patent propensity is greater during the mature phase.

The model suggests that the practice of building large portfolios of patents makes more sense for mature technologies. Gort and Klepper (1982) found that patenting rates were much higher during the "shakeout" phase of an industry than during the earlier phases, despite the higher innovation rates during the early phases (see Bessen and Meurer 2008, pp. 90-1 for a comparison chart).

Relatedly, Suárez and Utterback (1995) show that industry consolidation tends to follow the formalization inherent in a "dominant design."

5. Free mutual exchange of technical knowledge sometimes occurs during the early phase.

The early mechanics of the Industrial Revolution often shared designs (Meyer 2006). Even when mechanic/inventors such as Oliver Evans obtained patents, they would often not enforce them against other mechanics in their networks (Wallace 1978). 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). In some cases, the knowledge was only shared within a well-defined group, such as within the Bessemer patent pool; in other cases, knowledge was shared more widely, for example, through public trade journals, although even in these cases, only a limited audience would have had the experience and knowledge to understand and make use of the knowledge (Mokyr 2002). In many cases it is also evident that the inventors benefited by way of human capital, for example, in the Cleveland blast furnaces, the Cornish steam engines and the Bessemer steel pool, the inventors all worked as engineers.

Various scholars have also documented important modern instances of free knowledge exchange. Von Hippel (1987) finds knowledge exchange between steel mini-mills and user innovators in many fields (see also Schrader 1991), Meyer (2003) documents free exchange in the early personal computer industry and Cockburn and Henderson (1994) document information sharing in the early phases of the technology of blood pressure medications (but not in the late phase where innovations are potentially drastic). Much has also been written about free exchange of Open Source Software, which includes much key software of the Internet (see Bitzer and Schröder 2006). Where innovations are obviously tied to human capital, as with medical and surgical techniques, free exchange is seen as normal professional behavior. For example, attempts to patent surgical procedures were met with strong and quick opposition from the medical professional organizations.[14]

In some cases, the free exchange ends when the technology enters a different phase allowing drastic innovation. In other cases, competition remains "soft," sometimes because human capital constraints are supplemented by other market factors that limit the possibilities for drastic innovations. Nevertheless, the evidence is broadly consistent with the notion that mutual exchange of technical knowledge is common especially when the costs of communication and uncertainty over value limit the intensity of market competition.

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.

---

14. The response brought a change in the patent statute exempting these procedures from patent enforcement.

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.

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.[15] 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 ($= 2\,q\,L^*$), driving the price even lower. From this it follows that the drastic equilibrium will

15. 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.

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

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

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

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

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) $s_1 = \dfrac{(q_1-1)w - c'(x_1/q_1)}{\epsilon q_1 w}$ 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.

References

Aghion, Philippe, Mathias Dewatripont and Jeremy C. Stein, 2008. Academic freedom, private-sector focus, and the process of innovation, RAND Journal of Economics, v. 39(3), pp. 617–635.

Agrawal, Ajay 2006. Engaging the Inventor: Exploring Licensing Strategies for University Inventions and the Role of Latent Knowledge, Strategic Management Journal, Vol. 27, Issue 1, pp. 63-79.

Agrawal, Ajay and Rebecca Henderson 2002. "Putting Patents in Context: Exploring Knowledge Transfer from MIT," Management Science, Vol. 48, No. 1.

Allen, Robert C. (1983), "Collective Invention," Journal of Economic Behavior and Organization, 4, pp. 1-24.

Arora, Ashish and Alfonso Gambardella. (1994), "The changing technology of technological change: general and abstract knowledge and the division of innovative labour," Research Policy, 23, pp. 523-32.

Arrow, Kenneth. (1962) "Economic welfare and the allocation of resources for invention." in Richard R. Nelson, ed., The Rate and Direction of Inventive Activity: Economic and Social Factors. Princeton, NJ: Princeton University Press, pp. 609–625.

Arrow, Kenneth. (1969) "Classificatory Notes on the Production and Transmission of Technological Knowledge," American Economic Review, pp. 29-35.

Bartel, Ann P. and Frank R. Lichtenberg. 1987. "The Comparative Advantage of Educated Workers in Implementing New Technology," Review of Economics and Statistics, Vol. 69, No. 1 (Feb., 1987), pp. 1-11.

Bessen, James (2009), "Evaluating the Economic Performance of Property Systems," Review of Law and Economics, Vol. 5, Iss. 1, Article 1.

Bessen, James and Eric Maskin (2009), "Sequential Innovation, Patents, and Imitation," RAND Journal of Economics, 40(4) pp. 611-35.

Bessen, James and Michael J. Meurer (2008), Patent Failure: How judges, bureaucrats and lawyers put innovators at risk, Princeton, NJ: Princeton University Press.

Bitzer, Jürgen and Philipp J. H. Schröder, eds., 2006. The Economics of Open Source Software Development, Elsevier B. V.

Boldrin, Michele and David K.Levine. 2008. Against Intellectual Monopoly, Cambridge University Press.

Christensen, Clayton (1997), The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail. Harvard Business School Press.

Cockburn, Iain and Rebecca Henderson. 1994. "Racing to Invest? The Dynamics of Competition in Ethical Drug Discovery," Journal of Economics and Management Strategy, 3(3), pp. 481-519.

Cockburn, Iain and Megan MacGarvie. 2010 forthcoming. "Entry and Patenting in the Software Industry" Management Science.

Cohen, Wesley and Daniel Levinthal. 1989. "Innovation and Learning: the two faces of R&D," Economic Journal, 99, pp. 569-96.

Colyvas, Jeannette, Michael Crow, Annetine Gelijns, Roberto Mazzoleni, Richard R. Nelson, Nathan Rosenberg, and Bhaven N. Sampat 2002. How Do University Inventions Get Into Practice? Management Science, Vol. 48, No. 1, pp. 61-72.

Cowan, Robin and Dominique Foray. 1997. "The Economics of Codification and the Diffusion of Knowledge," Industrial and Corporate Change, 6(3), pp. 595-622.

Cowan, Robin, Paul A. David and Dominique Foray. 2000. "The Explicit Economics of Knowledge Codification and Tacitness," Industrial and Corporate Change, 9(2), pp. 211-53.

Darby, Michael R. and Lynne G. Zucker (2001) "Change or Die: the Adoption of Biotechnology in the Japanese and US Pharmaceutical Industries," Research on Technological Innovation, Management and Policy, v 7, pp. 85-125;

Darby, Michael R., Lynne G. Zucker and I.I. Welch (2001), "Going Public When You Can in Biotechnology" Working Paper.

Dasgupta, Partha and Paul David. 1994. "Toward a New Economics of Science,"Research Policy vol. 23(5), pages 487-521.

David, Paul. 1975. Technical Choice, Innovation and Economic Growth. Cambridge: Cambridge University Press.

Desmet, Klaus and Esteban Rossi-Hansberg. 2009. "Spatial growth and industry age," Journal of Economic Theory 144, pp. 2477–2502.

Epstein, Stephen R. (1998), 'Craft Guilds, Apprenticeship and Technological Change in Preindustrial Europe', Journal of Economic History, 58, pp. 684-713.

Foray, Dominique. 2004. The Economic of Knowledge, Cambridge: MIT Press.

Gallini, Nancy and Suzanne Scotchmer. "Intellectual Property: When is it the Best Incentive System?" in: A. Jaffe, J. Lerner, S. Stern, eds., Innovation Policy and the Economy, volume 2. (MIT Press, Cambridge, MA).

Gilson, R. J. 1999. The legal infrastructure of high technology industrial districts: Silicon Valley, Route 128, and covenants not to compete. New York Univ. Law Rev. 74 575–629.

Gort, M. and Klepper, S. 1982. "Time paths in the diffusion of product innovations," The Economic Journal, v. 92, p. 630.

Haber, Ludwig Fritz 1958. The chemical industry during the nineteenth century; a study of the economic aspect of applied chemistry in Europe and North America, Oxford: Clarendon Press.

Harhoff, D., J. Henkel and E. von Hippel. 2003. Profiting from voluntary information spillovers: How users benefit by freely revealing their innovations,Research Policy, 32, no. 10, pp. 1753-69.

Heller, Michael A. and Rebecca S. Eisenberg. 1998. "Can Patents Deter Innovation? The Anticommons in Biomedical Research," Science 1 May 1998: Vol. 280. no. 5364, pp. 698 - 701.

Henkel, Joachim, 2006. "Selective revealing in open innovation processes: The case of embedded Linux," Research Policy, vol. 35(7), pp. 953-969.

Hilaire-Perez, Liliane and Catherine Verna. 2006. "Dissemination of Technical Knowledge in the Middle Ages and the Early Modern Era New Approaches and Methodological Issues," Technology and Culture 47, pp. 536-565.

Hyde, Alan. 2003. Working in Silicon Valley: Economic and Legal Analysis of a High-Velocity Labor Market. M.E. Sharpe, Armonk, NY.

Jaffe, Adam B., Manuel Trajtenberg and Rebecca Henderson. 1993. "Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations," The Quarterly Journal of Economics, 108(3), pp. 577-598.

Jensen, R. and Marie Thursby (2001) "Proofs and Prototypes for Sale: the Tale of University Licensing," American Economic Review, v 91 n 1, pp. 240-59

Jeremy, David J. 1981. Transatlantic Industrial Revolution: The Diffusion of Textile Technologies Between Britain and America, 1790 - 1830s, Cambridge: MIT Press.

Jones, Charles I., 2005. "Growth and Ideas," in: Philippe Aghion & Steven Durlauf (ed.), Handbook of Economic Growth, volume 1, chapter 16, Elsevier, pages 1063-1111.

Kieff, F. Scott (2001) "Property Rights and Property Rules for Commercializing Inventions," Minnesota Law Review 85, pp. 697-754.

Kitch, Edmund W. (1977) "The Nature and Function of the Patent System," Journal of Law and Economics 20, pp. 265-90.

Klepper, Steven. 1996. "Entry, Exit, Growth, and Innovation over the Product Life Cycle," American Economic Review, 86(3), pp. 562-583.

Klepper, Steven and Graddy, Elizabeth. "The Evolution of New Industries and the Determinants of Market Structure." Rand Journal of Economics, 21 (1), pp. 27-44.

Kogut, Bruce and Udo Zander. 1992. "Knowledge of the Firm, Combinative Capabilities, and the Replication of Technology, Organization Science, 3(3), pp. 383-397.

Lach , Saul and Mark Schankerman (2003) "Incentives and Invention at Universities," NBER Working Paper 9727.

Lampe, Ryan and Petra Moser. 2009. "Do Patent Pools Encourage Innovation? Evidence from the 19th-Century Sewing Machine Industry," working paper.

Lerner, J. and J. Tirole. 2002. Some Simple Economics of Open Source. Journal of Industrial Economics, 50, no. 2, pp. 197-234.

Levin, Richard C., Alvin K. Klevorick, Richard R. Nelson, Sidney G. Winter, Richard Gilbert and Zvi Griliches. 1987. "Appropriating the Returns from Industrial Research and Development," Brookings Papers on Economic Activity, Vol. 1987, No. 3, Microeconomics, pp. 783-831.

Macleod, Christine and Alessandro Nuvolari. 2009. Inventive Activities, Patents and Early Industrialization. A Synthesis of Research Issues," working paper.

Mansfield, E., Schwartz, M. and Wagner, S. 1981. “Imitation Costs and Patents: An empirical study,” Economic Journal, v. 91, pp. 907.

Meyer, David R. 2006. Networked Machinists: Forging High-Technology Industries in Antebellum America. Baltimore: Johns Hopkins University Press.

Meyer, Peter B. 2003. Episodes of collective invention. BLS Working paper WP-368.

Meyer, Peter B. 2007. "Network of Tinkerers: A Model of Open-Source Technology Innovation," BLS Working Paper 413.

Mokyr, Joel 2002. The Gifts of Athena: Historical origins of the knowledge economy, Princeton University Press.

Moser, Petra. 2008. "Why Don’t Inventors Patent?," working paper.

Moser, Petra. 2009. "Do Patents Weaken the Localization of Innovations? Evidence from World’s Fairs, 1851-1915" working paper.

Murray, Fiona and Scott Stern. 2007. "Do formal intellectual property rights hinder the free flow of scienti c knowledge? An empirical test of the anti-commons hypothesis." Journal of Economic Behavior and Organization, 356 (23), pp. 2341-2343.

Nelson, Richard R. and Winter, Sidney G. 1982. An evolutionary theory of economic change. Cambridge, MA: Harvard University Press.

Nuvolari, Alessandro. 2004. “Collective Invention during the British Industrial Revolution: The Case of the Cornish Pumping Engine,”Cambridge Journal of Economics, May 2004, v. 28, iss. 3, pp. 347-63.

Romer, Paul M. 1990. Endogenous Technological Change, The Journal of Political Economy, Vol. 98, No. 5, Part 2, pp. S71-S102.

Rosenberg, Nathan. 1970. "Economic Development and the Transfer of Technology: Some Historical Perspectives," Technology and Culture, 11(4), pp. 550-575.

Rosenberg, Nathan. 1979. "Technological Interdependence in the American Economy," Technology and Culture, 20(1), pp. 25-50.

Schrader, Stephan. 1991. "Informal technology transfer between firms: Cooperation through information trading," Research Policy, 10, pp. 153-70.

Stein, Jeremy C. 2008. “Conversations Among Competitors,” American Economic Review, 98:5, pp. 2150–2162.

Suárez, Fernando F. and James M. Utterback. 1995. "Dominant Designs and the Survival of Firms," Strategic Management Journal, Vol. 16, No. 6, pp. 415-430.

Teece, David J. 1977, "Technology Transfer by Multinational Firms: The Resource Cost of Transferring Technological Know-How," Economic Journal, 87)346), pp. 242-261.

Teece, David J. 1986. "Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy," Research Policy, 15, pp. 285-305.

Thomson, Ross. 2009. Structures of Change in the Mechanical Age: Technological Innovation in the United States, 1790-1865, Baltimore: Johns Hopkins University Press.

Utterback, James M. 1996. Mastering the Dynamics of Innovation, Cambridge: Harvard Business School Press.

Utterback, James M. and Abernathy, William J. 1975. "A Dynamic Model of Process and Product Innovation." Omega, 3(6), pp. 639-56.

Vernon, Raymond. 1966. "International Investment and International Trade in the Product Cycle," Quarterly Journal of Economics, 80(2), pp. 190-207.

von Hippel, Eric. 1987, ‘Cooperation between Rivals: Informal Know-How Trading’, Research Policy, 16, pp. 291-302.

von Hippel, Eric. 1988. The sources of innovation. Oxford: Oxford University Press.

von Hippel, Eric and Ralph Katz. 2002. "Shifting Innovation to Users via Toolkits," Management Science, Vol. 48, No. 7, pp. 821–833.

Wallace, Anthony F.C. 1978. Rockdale: The Growth of an American Village in the Early Industrial Revolution. New York: Knopf.

Williams, Heidi, 2010. "Intellectual Property Rights and Innovation: Evidence from the Human Genome" NBER Working Paper 16213.

Winter, Sidney G. 1984, "Schumpeterian Competition in Alternative Technological Regimes," Journal of Economic Behavior and Organization, 5, pp. 287-320.

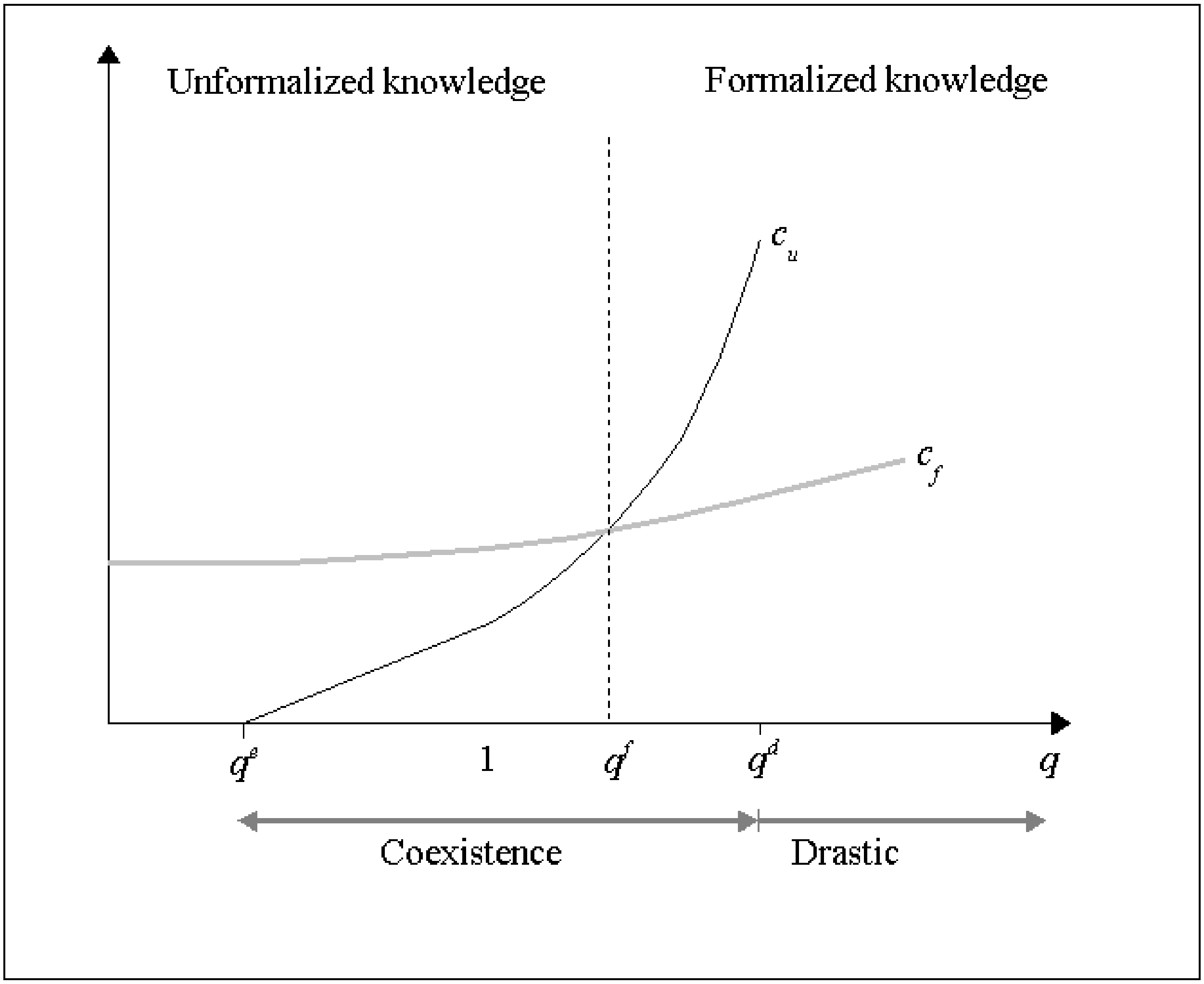
Zevin, Robert Brooke. 1971."The Growth of Cotton Textile Production After 1815" in Robert Fogel and Stanley Engerman, Reinterpretation of American Economic History, New York: Harper and Row.

Zucker, Lynne G., Michael R. Darby, Jeff S. Armstrong (1998) “Geographically Localized Knowledge: Spillovers or Markets?” Economic Inquiry, v 36 n. 1, pp. 65-86;

Zucker, Lynne G., Michael R. Darby, Jeff S. Armstrong (2001), “Commercializing Knowledge: University Science, Knowledge Capture, and Firm Performance in Biotechnology,” NBER Working Paper 8499;

Zucker, Lynne G., Michael R. Darby, M. B. Brewer (1998) “Intellectual Human Capital and the Birth of US Biotechnology Enterprises,” American Economic Review, v 88 n 1, pp. 290-306.

Figure 1.


Unformalized knowledge
Formalized knowledge
c_u
c_f
q^e
1
q^f
q^d
q
Coexistence
Drastic