Chapter 15

THE MARKET FOR TECHNOLOGY

ASHISH ARORA* *AND* ALFONSO GAMBARDELLA†

**Fuqua Business School*
Duke University, Durham
North Carolina, USA
†Department of Management and KITeS
Bocconi University
Milan, Italy

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Abstract

This chapter reviews the growing literature on the "market for technology," a broad term that denotes trade in technology disembodied from physical goods. The market for technology flourished during the nineteenth century in the United States. After several decades of relative decline, the market for technology has once again grown considerably in recent years, although the growth is uneven across sectors and across countries. Thus far, the literature has paid most attention to the supply of technology, and on the efficiency of market transactions in technology. A key contribution has been that the decision of firms to license depends on whether the revenues from licensing are higher than the rent-dissipation effect produced by increased competition in the licensor's product markets. The literature has featured several factors that condition the tradeoff between licensing revenue and rent dissipation. For instance, general-purpose technologies enable the potential licensors to sell technology in product markets distant from the product operations of the licensors, and thus are more likely to be licensed. Another stream of research has focused on the factors, such as intellectual property protection, that condition the efficiency of licensing contracts. The study of the demand for external technology is less developed, and is an open area for future research. Another exciting area for future research is the relationship between the product market and the market for technology, of which a special but important case is the division of labor between technology specialists such as biotech firms, and their customers downstream, in this instance, pharmaceutical firms. The area in the most urgent need of attention is research on the consequences of the market of technology, on the rate and direction of inventive activity, and on productivity growth. This will also require a deeper understanding of the microfoundations of the market for technology.

Keywords

division of labor, high-tech industries, markets for technology, patents, R&D

JEL classification: O3, L24, L26, M2

1. Introduction

A market for technology can yield important benefits. Trade in general expands the division of labor; trade in technology facilitates a division of labor in innovation. A division of labor yields the economies of learning and larger scale emphasized by Adam Smith, as well as a superior allocation of resources based on comparative advantage. An inventor need not acquire all the assets required to commercialize the invention and can instead license it to another firm better positioned to bring the innovation to market.[1] As well, a market for technology can lower entry barriers and increase competition in downstream product markets. Finally, in a world where commercialization is costly and slow, a market for technology diffuses technology more rapidly and increases productivity.

In this paper, we use the term "market for technology" in a broad sense. Strictly speaking, market transactions are arm's length, anonymous, and typically involve the exchange of a good for money. Most transactions for technology probably lack at least one of these criteria. For example, they may involve detailed contracts and be embedded within interfirm alliances, thus not be strictly anonymous, nor arm's length. A different perspective on markets analogizes them to centralized exchanges, including exchanges for trading contracts. Roth (2008) argues that well-functioning markets must be thick (many buyers and sellers), uncongested (each party can deal with many others on the opposite side), and safe (transacting outside or engaging in strategic behavior should not be profitable). The market for technology, at least as we know it, also fails the Roth test (Gans and Stern, 2010).

Imperfect though it might be, the market for technology has grown in recent years. Specific empirical estimates are discussed in greater detail below, but two empirical regularities are noteworthy. First, the market for technology has grown steadily in size since the mid-1980s. This is shown by the increase in annual licensing and royalty payments, the rise in the percentage of startups intending to license as a way to derive profit from some or all of their inventions, and the growing number of firms and organizations that specialize as intermediaries in the market for technology.[2]

Although the growth in the market for technology over the past quarter of a century marks a change over the relatively quiescent period that preceded it, this is not a secular trend. A series of papers, by Naomi Lamoreaux, Kenneth Sokoloff, and colleagues has demonstrated the existence of a vibrant market for patents and patent licensing in America during the mid- and late nineteenth century. However, by the early part of the twentieth century, patent licensing began to diminish. Winder (1995) describes the widespread use of licensing of inventions in harvesting machinery in North America in the late nineteenth century, but also notes that licensing diminished after the 1880s. International licensing was also found to be more important in the nineteenth century. Important inventions, such as the ammonia soda process patented by Ernst Solvay in 1861, were licensed extensively internationally. However, foreign direct investment by multinational corporations appears

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[1] Lamoreaux and Sokoloff (1996) show that growth in patent assignments before grant, their measure of trade in patents, coincided with growth in specialization in invention.

[2] These intermediaries include firms such as yet2.com, which runs an online site where technologies can be traded, Oceantomo, which runs online patent auctions, Intellectual Ventures, which acquires patent portfolios and contracts with inventors to develop inventions and technologies, and IP Bewertung, which provides several similar services in Europe. A yet different type of intermediary includes financial firms, such as Royalty Pharma, that acquire interests in future royalty streams.

to have been the dominant mode of international technology flows in the twentieth century (see also Chapter 3, Vol. 2).

Second, the market for technology is much more extensive in North America, and some limited evidence produced by Khan and Sokoloff (2004) suggest that this exists even during the nineteenth century. Figure 1, taken from Khan and Sokoloff (2004) indicates that over three quarters of patents granted in America in the 1870s and 1880s were assigned (indicating that the patent was traded), whereas fewer than one-third of patents in the United Kingdom were assigned or licensed. Since many more patents were granted in America, this gap is even more noteworthy. More recent data discussed below suggest that a gap, although perhaps smaller, remains.

These trends raise a number of related questions. Why has trade in technology been so limited in the twentieth century and what has caused the apparent growth since the 1980s? Why did a flourishing market for technology in nineteenth century America more or less vanish, only to rise again more than three quarters of a century later? Why is the market for technology more extensively developed in America than elsewhere? And finally, when do technology markets matter for the rate and direction of technical activity, for the evolution of industries, or for the rate of productivity growth? Any proposed answers must address the fundamental questions about the nature and functioning of the market for technology, namely who participates in them, under what conditions, and with what consequences.

We begin by clarifying what we mean by *markets for technology* in the next section. Section 3 reviews the microfoundations of the market for technology—why companies license technology and the factors that condition their demand for external technology. Section 4 provides some estimates of the size of the market for technology. Section 5 reviews the literature on the factors that condition the efficiency—and

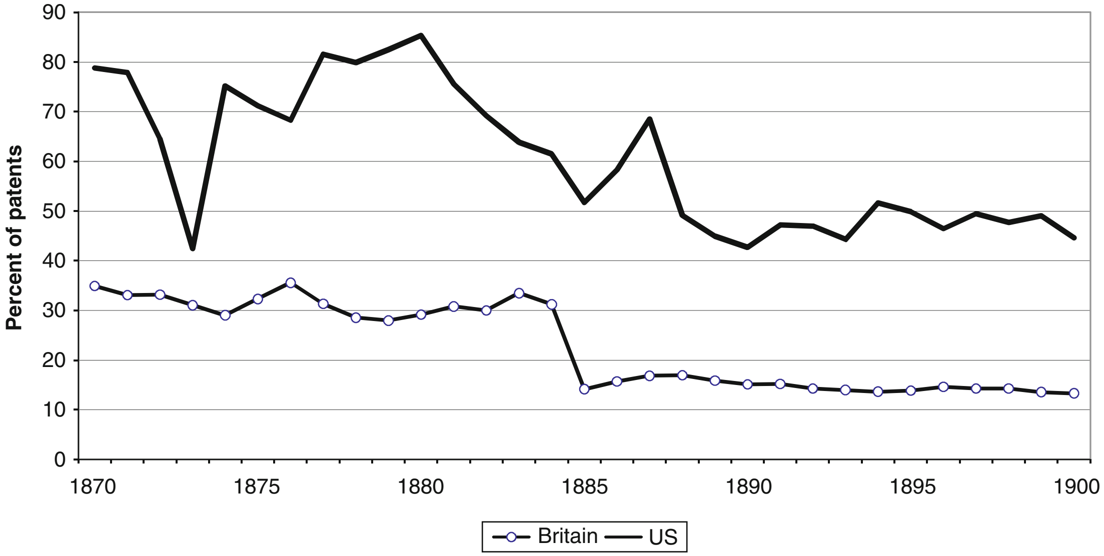

Figure 1. The market for inventions. The figure shows the percentage of patents assigned for the US, and patents assigned or licensed for the UK. Source: Khan and Sokoloff (2004).

hence the extent—of markets for technology, with particular focus on the role of intellectual property protection. Section 6 discusses the division of innovative labor that a market for technology can make possible. Section 7 concludes by highlighting unresolved questions and topics for further research.

It is also important to delineate some topics that we shall not discuss in this chapter. We shall not analyze university licensing. Though scholars have used it to examine issues related to licensing more broadly (e.g., Jensen and Thursby 2004; Mowery et al., 2001; Thursby and Thursby, 2002), the literature on university licensing is more closely related to how licensing does and does not comport with the objectives of the university. (See also Foray and Lissoni's (2010), this volume). Space constraints also preclude coverage of the extensive literature on R&D joint ventures and technology alliances. Finally, we shall only touch upon the literature on international technology licensing, mainly because it has been extensively covered in a number of places (see, for instance, Arora et al., 2008; Hoekman et al., 2005). Cross-licensing and other antitrust aspects of technology licensing are not covered for the same reason (see, for instance, Gilbert and Shapiro, 1997).

2. The market for technology: Definition and scope of our analysis

Technology comes in very different forms, and no general definition will fit. We will not define technology, treating it instead as an imprecise term for useful knowledge, rooted in engineering and science, which usually also draws on practical experience from production. Technology can take the form of "intellectual property" (e.g., patents), or intangibles (e.g., a software program, a design), or it can be embodied in a product (e.g., a prototype, a device like a chip designed to perform certain operations), or it can be a technical service.

The way technology is traded reflects the peculiar nature of technology as an economic asset. While pure forms of licenses (e.g., patent licensing or licensing of chip designs) are common, technology transfer is also frequently accompanied by the transfer of associated artifacts and know-how. In other cases, the supplier–buyer relationship is an R&D or codevelopment contract. The buyer may have to invest effort and resources to shape the technology to its needs (i.e., codevelopment), or fund the research of a liquidity constrained technology supplier.

Technology can also be exchanged through joint ventures and through the acquisition of firms. We exclude here these modes of interfirm technology flow.[3] Acquisitions, and to a lesser extent joint ventures, involve issues specific to the market for *firms*. Thus, though we shall contrast market transactions with processes within the firm, it is not to dispute the existence of hybrid forms but to sharpen the exposition. We also distinguish between ex-ante contracts (i.e., contracts for R&D) and ex-post contracts (i.e., contracts for existing technology). The distinction is especially important from a transaction cost perspective, since ex-ante contracting potentially creates greater contracting problems.[4]

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[3] Interfirm movement of technology can also occur through labor mobility, which we also ignore.

[4] Barring Mowery's study of contract R&D firms and their decline (Mowery, 1984), the empirical literature on contract R&D is limited. Mowery emphasizes the need for potential buyers of R&D services to have considerable in-house capability. He also notes that if contracts are incomplete, the buyer becomes increasingly vulnerable to opportunistic behavior as the R&D supplier progressively acquires more buyer-specific knowledge. Arora and Merges (2004) emphasize the reverse; as the buyer learns the supplier's know-how, it renders the supplier vulnerable to holdup.

Table 1
A simple typology of markets for technology

	Existing technology	Future technology or component for future
Horizontal market/ transactions with actual or potential rivals	Union carbide licensing unipol polyethylene technology to huntsman chemicals	Sun licensing Java to IBM; R&D partership between rivals (e.g., see Hagedoorn, 2002)
Vertical market/licensing to nonrivals	Licensing of IP Core in semiconductors	R&D agreements or other technological alliances; Affymax licensing combinatorial drug discovery technology to pharmaceutical companies

In sum, a market for technology refers to transactions for the use or creation of technology. It includes transactions ranging from full technology packages (patents and other intellectual property, along with know-how and services) to bare-bones patent licensing. It also includes transactions involving knowledge that is not patented but embodied in artifacts such as designs, software, or technical services. It can involve parties in the same product markets or vertically related suppliers and buyers, and the contracts involved can vary in simplicity and design. It can involve the transfer of existing knowledge or contracts for the creation of new knowledge. Most of the literature reviewed below, both theoretical and empirical, focuses on some subset of the market for technology.

Table 1 summarizes our definition of the markets for technology in the form of a simple two-by-two typology, along with canonical examples for each case. Technologies can be sold to firms in the same product-market (horizontal transactions) or to firms operating downstream (vertical markets). The market for technology can involve existing technologies that are licensed, or it can be the market for contract R&D and associated alliances, more properly thought of as the market for "future" technologies, sometimes called the "market for innovation."

3. The microfoundations: Why do companies license?

3.1. Gains from trade

The literature has tended to separate analysis of why firms choose to license out and license-in technology. We follow this division here. However, the conceptual starting point is with the gains from trade. Gains from trade in technology have three sources. First and foremost, technology is "infinitely expansible," to use the term coined by Dasgupta and David (1994). Simply put, it is a good thing if one does not have to reinvent the wheel. Thus, expanding the use of technology will create gains which have to be balanced against the potential loss due to the decreased exclusivity of access. This aspect is particularly salient (and well understood as such) in international technology licensing, and in the discussion of general-purpose technologies (GPT).[5]

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[5] In passing, we note that this point is more commonly discussed using the related concept of nonrivalry. However, in most cases of interest, technology is in fact a rival good because exclusive access to it is more valuable than access shared with others. Even when it is a rival good, however, technology can be infinitely expansible in the sense that a wheel does not have to be reinvented.

The second source of gains from trade is comparative advantage. As discussed in the context of a division of labor, sometimes the inventor of a technology is not best equipped to develop or commercialize it. Engaging in commercialization may even retard innovation, by diverting attention and changing the nature of the organization.[6] Licensing to another firm with a comparative advantage in manufacturing and marketing will yield gains to both parties.

The third source of gains is more obvious. For instance, a firm may develop a technology that it does not wish to use but which is applicable elsewhere, and can gainfully license it (or sell it). Some licensing is undoubtedly of this nature, but it does not require much explanation. There are few studies that explicitly take a "gains-from-trade" approach to analyzing the market for technology. Instead, most studies analyze either why a firm licenses its technology to others, or, less frequently, when a firm uses external technology (in-licensing).

3.2. Supply: Determinants of technology licensing

The literature has analyzed a variety of reasons for firms to license their technology. The early literature on licensing focused on the optimal licensing behavior of the monopolist inventor once it has developed and patented a new technology or production process (see Gallini and Wright, 1990; Kamien and Tauman, 1986). Katz and Shapiro (1986) analyze the optimal number of licensees for a single technology holder who does not compete in the product market. Rockett (1990) develops a model where the technology holder also produces the product but faces entry after its patents expire. He also shows that a technology holder will optimally license an inefficient potential entrant to foreclose entry by a more efficient firm. Gallini (1984) also provides a model where licensing is strategically used to deter entry.

In addition, firms license as parts of standard-setting bodies or to promote their technology as a dominant standard (see, e.g., Shapiro, 2000). Firms may choose to license some technology to provide incentives to potential adopters. For instance, Corts (2000) provides a model where a firm may optimally commit to innovate by licensing the production of the ancillary product to another firm, even when licensees are inefficient. The intuition is that innovation may require substantial redesign of the ancillary product, entailing costs that an integrated firm will internalize. When potential adopters have to coinvest for an innovation to be successful, an integrated firm may be tempted to free-ride on their investment. Knowing this, potential adopters are reluctant to coinvest. A firm can credibly commit to innovate, therefore, by licensing to other producers of the ancillary products. Similarly, Shepard (1987) shows that firms may license to enhance demand, in essence protecting potential buyers against having to deal with a monopolist supplier.

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[6] Lamoreaux and Sokoloff (2005, p. 17) relate the story of Elmer Perry, who started The Sperry Electric Light, Motor, and Car Brake Company in 1883, to commercialize his dynamo. "Although the company launched Sperry's career as an inventor, it left him little time and energy for creative pursuits. Indeed, the 19 patents he applied for during his 5 years with the company amounted collectively to half his *annual* average over a career as an inventor that stretched from 1880 to 1930."

3.2.1. Licensing revenue versus rent-dissipation effects

The foregoing papers have usually assumed a single technology holder and that the technology holder is also the monopoly producer of the good. They ignore competition among technology holders and also typically ignore the very likely situation that the technology holder competes with other producers in the product market. These simplifying assumptions imply that licensing is typically not profitable, but instead can only be attractive to serve some other strategic purpose. However, the example of firms such as Texas Instruments, IBM, and Union Carbide, which earned millions of dollars from licensing technology, points to the possibility that even large, well-established, firms may directly profit from their technology by licensing it, rather than merely embody it in their own output.

Arora and Fosfuri (2003) develop a framework to understand the decision of firms to sell technology, and how product market and technology market competition condition this decision. In their model, multiple technology holders compete, both in the technology market and in the product market. Technologies are not perfect substitutes for each other, and neither are the goods produced from the technology. In deciding whether to license or not, the technology holder has to balance the revenue from licensing and the rent-dissipation effect produced because licensing will increase product-market competition. As a result, factors that enhance licensing revenue or that reduce rent dissipation will encourage licensing.

This tradeoff depends upon competition in the product market. If the licensee operates in a "distant" market, rent dissipation is small compared to when the licensee is "nearby." For example, the licensee may operate in a geographical market in which the licensor finds it costly to operate, for example, because the licensor does not have the complementary downstream assets. Similarly, the technology could be used for a different type of product that the licensor may not produce. Arora and Fosfuri note that product-market competition enhances licensing because rent dissipation falls faster than licensing revenues as product market competition increases. Indeed, as is well known, a monopolist will not license. Consistent with this, Lieberman (1989) finds that licensing was less common in concentrated chemical products, and the limited licensing that did take place was by outsiders (nonproducers and foreign firms).

Arora and Fosfuri also point out that licensing is more likely when products are homogeneous rather than differentiated. If products are differentiated, a licensee is closer in the product space to the licensor than to other producers, so that the rent dissipation felt by the licensor is greater than if the product is homogenous. Put differently, by licensing, a technology holder imposes a greater negative (pecuniary) externality on other producers when the product is homogenous. Consistent with this, Fosfuri (2006) finds that licensing is lower in markets where technology-specific product differentiation is high.

The Arora–Fosfuri framework also implies that smaller firms are more likely to license, because they suffer less from the rent-dissipation of additional competitors. The logic is apparent in the extreme case in which the licensor has no stakes in the downstream markets, and thus has no product-market rents to worry about. This is also consistent with the observation that technology suppliers often do not produce in the product markets for which they supply technology, as is the case in biotechnology (Arora and Gambardella, 1990), semiconductors (Hall and Ziedonis, 2001), software security (Giarratana, 2004), and chemical engineering (Arora and Gambardella, 1998). This implication is also consistent with Teece (1986,1988) in that control of downstream assets makes licensing less likely. The point is confirmed by McGahan and Silverman (2006), Ford and Ryan (1981), and more recently by Kollmer and Dowling (2004), who show that licensing is less likely if firms have downstream assets. Similarly, Fosfuri (2006) finds a negative effect of downstream assets on licensing in chemicals.[7]

This is exemplified by the different ways in which BP Chemicals approached acetic acid and polyethylene licensing in the 1980s. In acetic acid, BP Chemicals had strong proprietary technology, but licensed very selectively, typically only in markets it would otherwise be unable to enter. By contrast, in polyethylene, BP had less than 2% of the market. Although BP had good proprietary technology as well, there were several other sources of polyethylene technology. Accordingly, BP licensed its polyethylene technology very aggressively, competing with Union Carbide which was the market leader in licensing polyethylene technology.

By relaxing the assumption of a single technology holder, Arora and Fosfuri (2003) point to the importance of competition among technology suppliers. For instance, BP initially tried not to license even polyethylene technology in Western Europe, where it had a substantial share of polyethylene capacity. However, other licensors continued to supply polyethylene technology to Western Europe, resulting in BP losing potential licensing revenue without any benefits in the form of restraining entry. BP's response was to also offer its technology for license. The direct implication is that the market for technology feeds on itself: competition from one technology holder promotes licensing by others.

3.2.2. Licensing decisions in the long-run

Gambardella and Giarratana (2009) generalize the Arora and Fosfuri framework by emphasizing the interplay between the generality of the technology and the fragmentation of the product markets. Generality of the technology makes it attractive to "distant" user firms, which implies that revenues from licensing can be earned from firms in product markets different from that of the technology holder. Because the markets are distant in product space, the rent dissipation is small, which raises the incentives to license.

Gambardella and Giarratana (2009) jointly consider both the licensing decision and the decision on the range of product markets that the technology holder will enter. The key assumption is that technology can be deployed in more product markets than is profitable for the technology holder to serve directly. The contrast between the generality of technology and the narrowness of product market assets is significant. Several scholars have observed that firms frequently "know more than they make" (Brusoni et al., 2001; Gambardella and Torrisi, 1998), suggesting that technology has broader economies of scope than marketing and manufacturing assets, which creates opportunities for licensing. This logic applies a fortiori to GPT, which are so broadly applicable that few firms are likely to exploit all applications.

In the longer run, the decision to supply technologies depends upon the market for downstream assets involved in the commercial application of technology. The interactions between the two can lead to complex patterns, as illustrated by the history of licensing in farm machinery in the United States between 1850 and 1910 (Winder, 1995). Winder (1995) shows that in the 1850s there was considerable technology licensing in this industry even though a typical harvester had many different components,

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[7] However, firm size also comes with broad scope of activities, and thus the relationship between size of the firm and probability to license out is U-shaped: small firms and large firms are more likely to license out their patented inventions, a finding also reported by Zuniga and Guellec (2008) and Motohashi (2008). Larger firms may be more likely to develop technologies in which they have limited interest, or operate in markets where they face competition from other licensors.

each individually protected by patents. Fragmentation of the product market, due to high transport costs, meant that innovators would typically license technology to producers in geographically distinct markets. The result was that there were many producers in a market, and a typical harvester embodied innovations from multiple innovators.

Over time, this modular system changed to one that was like many vertical silos, with competition between silos, but with licensing still prevalent within silos (e.g., type 1 harvester had many components, with different firms producing this type of harvester licensing designs and technologies to each other, but not to producers of type 2 harvesters). By the 1890s, this licensing regime disappeared and product markets consolidated, with a couple of dominant producers controlling both the technology and production.

Winder (1995) links the disappearance of the licensing regime to changes in technology (steel instead of iron, which mean that small foundries could no longer produce parts and larger scale, steel-using, factories were required), which in turn meant that small machinery producers had higher costs. However, Winder's explanation ignores the reductions in transport costs and greater integration of hitherto geographically distinct markets, which were likely very important. As markets integrate, reducing the "distance" between markets, the incentives for larger scale production are enhanced and the incentives to license are reduced. Put differently, the asymmetry between the scope implied by technology and that implied by the production and marketing capabilities of the firm diminished, reducing the gains from trade from licensing. Additional support can be found in Lamoreaux and Sokoloff (2005), who note that as US market integrated in the latter part of the nineteenth century, independent inventors that had hitherto sold multiple licenses for their invention, while also manufacturing for their local market, were forced to either license to a single firm or contemplate manufacturing for the entire national market.

Modeling the interaction between the product market and the technology market, plus the possible coevolution of the two, is an area ripe for additional research. Given the daunting complexity of theoretical models, simulation-based models may provide useful insights (see, for instance, Malerba et al., 2008). Focusing on the long-run, decisions regarding entry into product markets and technology markets naturally leads to the literature on specialization and division of labor, which we cover in Section 6.

3.3. Demand

The demand for technology licenses has received less attention in the literature compared to the willingness or desires of firms to license. We ignore factors that condition the demand for technology in general, and focus on the factors that condition the demand for external technology.

One situation in which firms license external technology is when their internal efforts do not bear fruit (or the firm did not invest in research in the first instance). For instance, Higgins and Rodriguez (2006) show that pharmaceutical firms with thinner product pipelines were more likely to acquire external technology. This perspective, though undoubtedly correct, is also limited. Technology differs from conventional goods in an important but underappreciated respect: Knowledgeable buyers of technology are at a marked advantage compared to buyers that lack such knowledge. This means that buyers have to be technically sophisticated themselves, so that the demand for technology may be confined to small subset of firms, at least until the technology itself becomes highly standardized.

3.3.1. Absorptive capacity

It is now standard in the literature to refer to the notion of "absorptive capacity" to mean that the ability of a firm to use technology depends on its internal technical competence. Cohen and Levinthal (1989) develop a model in which this internal competence is related to whether (and how much) the firm conducts R&D internally. There is no licensing in Cohen and Levinthal's model, and the external technology is absorbed through spillovers from the research of other firms. However, the idea of absorptive capacity can be applied quite directly in developing a firm-level demand for technology. In a similar spirit, Rosenberg (1990) asks "Why firms do basic research (with their own money)?" He notes that an important reason for making these investments, despite the low levels of private appropriability of basic research, is that by performing basic research firms are better equipped to understand knowledge produced by others.[8]

Arora and Gambardella (1994b) develop these ideas further. They distinguish between "ability to utilize" and "ability to evaluate." The ability to utilize denotes the ability of a firm to extract value from the technology, and requires technical competence as well as downstream assets such as manufacturing and marketing. The ability to evaluate denotes the ability of the firm to judge the value of the technology. This is a second dimension of absorptive capacity, which is more closely related to the technical and scientific capability of the firm. While both these dimensions of absorptive capacity increase the value that the firm can extract from external technology, they have different implications for the demand for external technology. Arora and Gambardella (1994b) show that firms with greater ability to utilize will demand more external technologies (i.e., more likely to license). However, firms with higher ability to evaluate will demand fewer external technologies, even though the expected value for the technologies that they demand will be higher. The intuition for this result is that technology acquisition is like purchasing a real option, in which the licensing fees paid to acquire a technology are substantially smaller than the investments in development, manufacturing, and marketing to use the technology. Firms that are better able to judge will optimally acquire fewer options.

3.3.2. Internal R&D and the demand for technology: Other considerations

Internal R&D has another, more obvious, impact on the demand for external technology. Consistent with Mowery's observations about the danger of buyers of contract R&D services becoming "locked in" to their technology suppliers, Gans and Stern (2000) develop a model where the potential buyer engages in R&D to increase bargaining power in licensing negotiations (see also Ulset, 1996). Insofar as internal efforts are successful, this will reduce the demand for external technology. Sometimes, learning how to use and maintain external technology may require as much effort as creating the technology itself, as is sometimes the case with software. In such cases, a firm may optimally choose to develop technology internally even

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[8] Many studies use the idea of absorptive capacity, broadly defined. For instance, Forman et al. (2008) use data on almost 87,000 US establishments and look at their decision to adopt advanced Internet technologies. They find that establishments with a larger number of software programers are more likely to adopt the technology. However, when the establishment is located in large cities, the effect of internal programers on adoption is smaller. In other words, internal programers are complementary to external technology, but less so in bigger cities, perhaps because larger cities offer greater possibilities of using external software programers to adapt Internet technologies for the firm's needs. The point is that if firms want to buy the technology, they need to have internal competences in the broadly defined area of the technology.

when it is possible to license in external technology. When the internal R&D effort becomes significant enough, the firm may choose to develop the technology internally instead. Cohen and Kepler (1992) develop a model in which the benefits of investing in R&D are proportional to sales. Though they do not analyze licensing, the small firms in their model are better off licensing external technology while larger firms may prefer to develop technology internally. More broadly, Arora and Gambardella (1994a) note that because technology buyers are also likely to have internal R&D, the dynamics of technology markets are more complicated, which is a potentially fruitful area for future research.

Motivated by the "make-buy" perspective, in which internal R&D is a substitute for external technology (Pisano, 1990; Williamson, 1985), there are a number of studies that estimate the demand for licensing, usually as part of an effort to determine whether licensing is a substitute for internal R&D or not. For the most part, these studies find that internal R&D and licensing are complements rather than substitutes. For instance, Cassiman and Veugelers (2006) find that Belgian firms view R&D and external technology acquisition as complements. The complementarity is especially marked in firms that invest in basic research.

Firms may also choose not to license in technology for strategic reasons. Rotemberg and Saloner (1994) develop a model where a firm rationally chooses a Not-Invented-Here strategy of explicitly excluding external technology to provide incentives to its own employees to innovate. While there is much discussion of the Not-Invented-Here syndrome among practitioners and industry observers, to our knowledge there is little research in economics on the topic, the reasons why firms may be affected by it, and its consequences.[9]

4. The size of the market for technology

4.1. The world market for technology since the mid-1990s

Arora et al. (2001a) review studies that quantify the size of the market for technology in the 1990s. Despite different data sources and methods, the estimates provided by these studies are remarkably similar: In the mid-1990s, the annual value of transactions in the market for technology was $25–35 billion in the United States, and about $35–50 billion globally.

A survey by the British Technology Group, based on interviews of 133 R&D intensive firms and 20 universities in Europe, North America, and Japan, estimated that expenditures on technology licenses amounted to 12%, 5%, and 10% of the total R&D budgets, respectively, for each region. These percentages were also used to estimate the order of magnitude of the size of the markets for technology in each of the three regions. In 1996, OECD figures indicate that North America spent $027 billion on R&D, the European Union $132 billion, and Japan $83 billion. This implied that the size of the market for technology was approximately $25 billion in North America, $6.6 billion in Europe, and $8.3 billion in Japan, and would put the total world market for technology at about $40 billion in the mid-1990s.

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[9] There is little doubt that here practice is far ahead of scholarship. For instance, a leading pharmaceutical firm, Glaxo, has explicitly declared that it will rely upon external technology for a significant fraction of its products in the future. The actual behavior of other pharmaceutical firms indicates that Glaxo is not an exception.

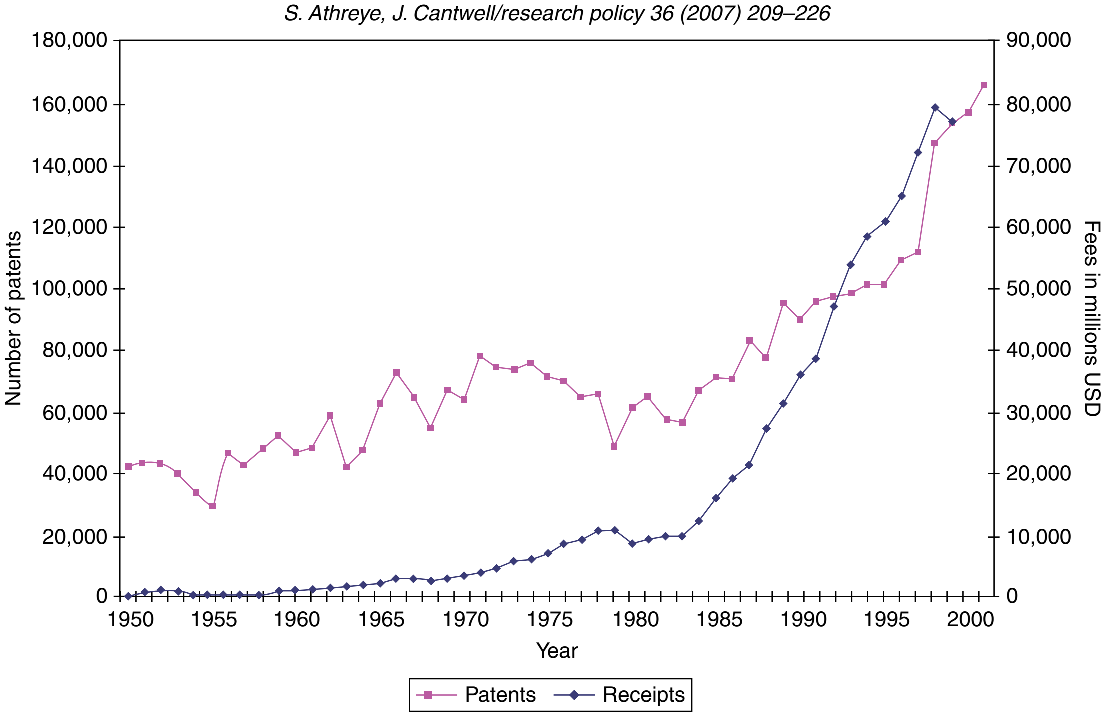

Figure 2. Growth in non-US held patents and worldwide royalty and license and revenues. Source: Athreye and Cantwell (2007).

Since Arora et al. (2001a), two additional estimates have been generated. Athreye and Cantwell (2007) analyzed trends over time in international royalty and licensing revenues worldwide between 1950 and 2003. For 1950–1970, they used the IMF Balance of Payments Yearbook and for 1970–2003 they used the World Development Indicators (WDI) database. Figure 2 reports their chart of the world licensing payments and receipts between 1950 and 2003. The estimates reported by Athreye and Cantwell tend to be on the higher end of spectrum. For example, they set the world market for technology at $55–60 billion in the mid-1990s. For 2000, they size the world market for technology at $90–100 billion.

The Athreye and Cantwell figures also indicate strong growth in the international flow of licensing fees and royalties. Adjusting for changes in coverage, we computed that royalty payments and receipts increased at 8.7% and 7.0% in 1980–1990 and 9.8% and 5.6% in 1990–2003, substantially higher than the growth rate of the world GDP, which was 3.3% on average for 1980–1990 and 2.8% for 1990–2003.[10]

The data on international royalty flows suggest that markets for technology have grown over the last two decades. However, there are two potentially offsetting effects. First, the bulk of these transactions

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[10] See Table 4.1 of the World Development Indicators (2005).

may be among affiliated entities rather than market transactions. Data from the United States indicate that transactions among unaffiliated entities account for fewer than one-third of the licensing and royalty receipts of American firms. For instance, in 2007, the latest year for which data were available,[11] the total receipts of US firms from royalties and licensing fees for industrial processes and products amounted to $37.4 billion. Of this, $7.9 billion, or about 21%, came from unaffiliated entities. The share of unaffiliated transactions has fluctuated over the years, and no clear trend is discernable, which suggests that the cross-border market for technology is considerably smaller than the $100 billion reported by Athreye and Cantwell.

A second offsetting effect is that the figures for licensing fees and royalties used in Athreye and Cantwell (2007) include payments for packaged software, trademarks, and copyrights. Data from the United States suggest that although licensing and royalty receipts have grown strongly, at over 10% per annum on average, payments for industrial processes and products, which correspond mostly closely to the market for technology, have grown far more slowly. Correspondingly, the share of payments for industrial processes and products has steadily dropped, from around 70% in 1987 to 33% in 2007. However, Figure 3 shows that even accounting for these, cross-border flows of technology between unaffiliated parties has grown steadily.

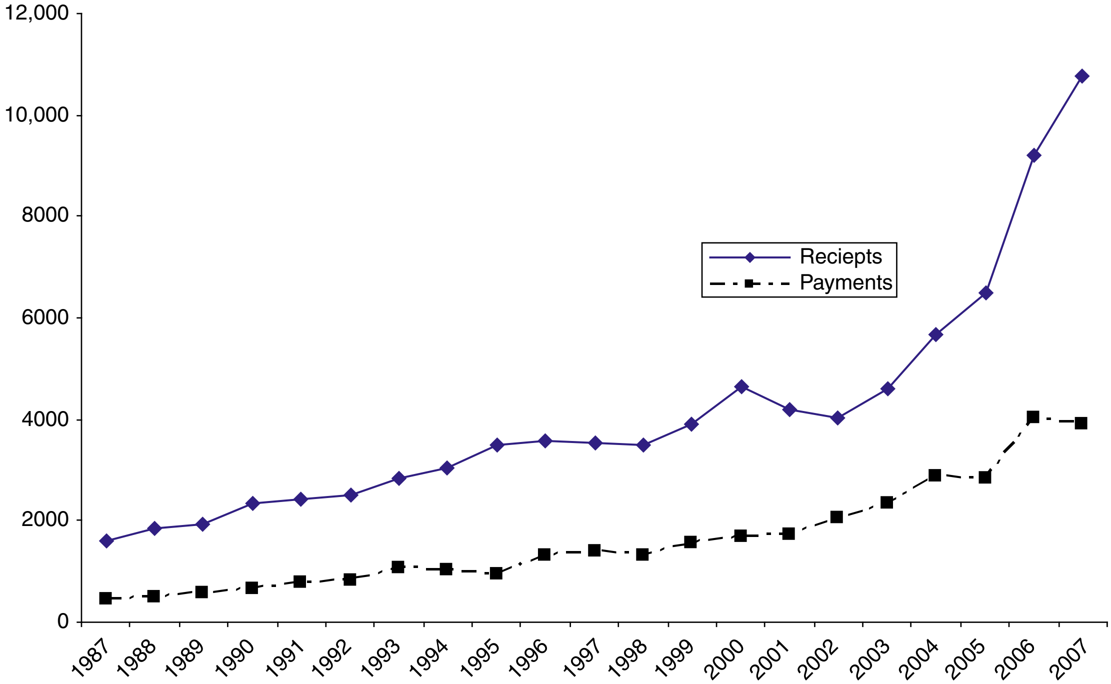

Figure 3. International licensing royalties for industrial processes, unaffiliated transactions only, United States, 1987–2007, $ millions. Source: Table 4.22. Royalties and License Fees, 2007, US http://www.bea.gov/international/intlserv.htm

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[11] See Table 4.22. Royalties and License Fees (2007). US http://www.bea.gov/international/intlserv.htm

The most authoritative estimates of the size and growth of markets for technology, although only for the United States, are provided by Robbins (2006), based on confidential tax data. Robbins estimates that domestic income from licensing intellectual property was \$92 billion in 2002. She follows Arora et al. (2001a) and assumes that the proportion of technology licensing, as opposed to licensing of trademarks, copyrights, and packaged software, is the same as that in cross-border transactions, which implies that licensing of industrial processes amounted to \$66 billion.[12] Of this, about \$50 billion was earned domestically, and the remaining was earned from overseas. If one assumes that the United States accounts for 60% of the global market for technology, this would imply that the global market for technology in 2002 was about \$100 billion. Using the same method, Robbins produces estimates of \$27.4 billion for 1995, \$29.4 billion for 1996, and \$31.8 billion for 1997 for US corporate supply of IP-licensing of industrial processes, which are very close to the estimates provided by Arora et al. (2001a) using transaction data. These imply a growth rate of about 13% per annum, somewhat faster than the growth rate estimated by Athreye and Cantwell.

A recent OECD survey confirms both that established firms have increased their propensity to license-in and to license-out new technologies, and that the market for technology is disproportionately larger in the United States (Sheehan et al., 2004). The survey, which was administered in 2003, covered 105 firms in Europe (68 firms), North America (20), and Asia-Pacific (17, mostly from Japan). Most firms were large—only 20% had fewer than 1000 employees. Almost 60% of the firms interviewed reported increased inward and outward licensing during the previous decade. Moreover, North-American and Japanese firms reported licensing more frequently than European firms, consistent with the findings of the British Technology Group survey discussed earlier.

In sum, the evidence suggests that markets for technology are of significant size and have grown over the last decade. They appear to be the most extensive in the United States, followed by Japan, with Europe lagging both. Undoubtedly, the robust economic growth over this period, particularly in information and communication technologies, and the huge growth in research and development expenditures in life sciences have contributed greatly to the growth of technology markets. Since 2002, ICT growth has slowed, as have investments in life sciences research and development. It is highly likely, therefore, that markets for technology have also grown more slowly since then, and perhaps even declined somewhat.

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[12] Cockburn and Henderson (2003) asked 81 IP managers from a range of industries to estimate the value of IP assets. These estimates implied that patents, trade-secrets, and know-how account for about three quarter of the value of intellectual property, and trademarks and copyrights for 18% and 9%, respectively. If one believes that licensing of industrial processes involves licensing of patents, know-how, and trade-secrets, then Arora et al. (2001a) and Robbins (2006) effectively assume that the latter account for about 72% of all licensing royalties. In other words, the share of licensing of industrial processes in all licensing is remarkably close to the estimated share of patents, know-how, and trade-secrets in total intellectual property reported in Cockburn and Henderson.

4.2. Firm-level evidence

A 2003 OECD survey indicates that established companies worldwide are more likely to license-in and to license-out in the pharmaceutical, and the information and communications technology (ICT) industries (Sheehan et al., 2004). Licensing has been common in the chemical industry, at least since World War II (e.g., Anand and Khanna, 2000; Arora and Gambardella, 1998; Cesaroni, 2003). There is a large literature that has studied licensing between biotech firms and pharmaceutical companies (see, for instance, Gambardella, 1995). A more recent survey (Zuniga and Guellec, 2008) reports a U-shaped relationship, with both very small and very large firms indicating higher rates of out-licensing than firms in between. Zuniga and Guellec (2008) analyze a representative sample of patent-filing firms in 2007: 600 European and 1600 Japanese. The results show that patent licensing is widespread among patenting firms. Nearly a fifth of the European companies license patents to nonaffiliated partners, whereas more than a quarter do so in Japan.

Zuniga and Guellec (2008) find that among the European and Japanese firms that patent and license, a very large fraction of patents are licensed. For instance, nearly 50% of the European firms that did some licensing to unaffiliated parties report that they licensed more than 80% of their patent portfolio, while of Japanese firms that report some licensing to unaffiliated parties, around 40% claim to have licensed more than 80% of their portfolio. The survey further finds that although both cross-border licensing and cross-licensing are important, neither type of licensing accounts for all the licensing activity reported. Nearly, two-thirds of European and over 85% of the Japanese firms that license report that less than 20% of their licensing is cross-border. Nearly, 80% of European firms, and a slightly higher share of Japanese firms, report that less than 20% of their patents involved in licensing are cross-licensed. Thus, the licensing activity reported in this survey is more than simply cross-licensing and is further supported by the finding that over 40% of the European firms that license report that know-how transfer is involved in more than 20% of their licensing deals, and a third of the firms report that know-how transfer was involved in more than 40% of their licensing deals. Japanese firms appear to participate less intensively in patent licensing deals that also involve know-how transfer: only a quarter report that know-how transfer was involved in more than 20% of their licensing deals, and only one-sixth report that more than 40% of their licensing deals involved know-how transfer.

Furthermore, licensing activity appears to have increased between 2003 and 2006. Of the European firms reporting licensing in 2006, about 45% reported an increase in licensing revenues or the number of licensing deals, although only 8% reported a dramatic increase in either. Only 3% of the firms reported a decrease, with most (slightly more than 50%) indicating no change.

Overall, the data indicate that licensing transactions have increased since the mid-1990s, with some evidence that non-American firms are catching up with their American rivals. The data also indicate that, though substantial in absolute value, licensing as an activity is still not central to the innovation process, although with some notable exceptions such as biopharmaceuticals. Nor, once again with notable exceptions such as chemicals and petroleum refining, is licensing the dominant form of technology flows across firms. These findings, that technology markets have grown but are still limited in extent over industrial and geographical scope, necessitate the discussion of the factors that are responsible.

5. Factors that condition the market for technology

Following Arrow (1962), economists have emphasized asymmetry of information as the key barrier to trade in technology. Though asymmetric information may well be important, lack of information, or uncertainty, is surely a more important problem. Whereas asymmetric information creates problems when agents behave in self-interested ways, the nature of technology creates problems for a market for technology even absent such behavior. Uncertainty about technical success and commercial applicability, the difficulty in specifying a technology and valuing it, and the challenge of locating potential trading partners may be more serious problems than asymmetric information. In plain words, lack of information may be a much bigger problem than differences in access to information. For the most part, however, the literature has paid insufficient attention to the problem of insufficient information, with disproportionate attention to the issue of asymmetric information.

5.1. Cognitive limitations

Uncertainty poses a significant barrier to the market for technology. Unlike specific products or services, technology is hard to pin down. This is especially true when technology is not codified, and is embedded in people or machines. For example, improvements in a production process or in a service may be hard to define and codify with precision. In these cases, the object of the transaction is ill-defined to begin with, and this ambiguity makes it harder to trade in the improved process.

The difficulties are not only contractual. Discovering who has relevant technology and the price at which they may make it available (if at all) is also difficult. Understanding what they have and how to use it amplifies the problem. Conversely for a seller, identifying potential buyers can be problematic, and once a prospective partner has been identified, settling on the price can be no less challenging.

Problems of price discovery are not unique to markets for technology. For instance, a common approach used in the valuation of startup firms is the price paid for comparable firms. Although no two firms are identical, often they are similar enough for one to be used as a benchmark. However, using comparables begs the question inasmuch as it assumes a reasonably liquid market for acquiring startups. Lamoreaux and Sokoloff (1996, 2001) describe how the rise of a market for patents in the United States in the nineteenth century involved the growth of supporting institutions such as intermediaries that helped spread information about patents (e.g., patent agents, patent lawyers, and even publications such as the Scientific American, which reported available patents for sale). Their work underlines the important role that patents play in this market. Patents provide a document that clearly defines the object of exchange, and represents a focal point of the transaction. Second, patents clearly define the intellectual property rights of the two parties, thus avoiding potential ambiguities. Third, the patent offices themselves, along with patent agents and lawyers, can be a focal institution for organizing technology trade.

One problem in the market for technology is that the knowledge to be traded is often partially inarticulable (Winter, 1987) in part because the knowledge is largely based on empirical observation and experience, rather than understood through general principle. Arora and Gambardella (1994a) argue that the increase in the extent to which industrial technologies are based in science (including engineering sciences), and the use of advanced instruments and computers is reducing the fraction of "inarticulable" technology. Thanks to advances in computer technology, including software, many technical problems (e.g., in design, semiconductors, biotechnology, and many other industries) can be defined in logical terms (e.g., mathematical language) and captured in software. Interestingly, there are useful synergies with patents in facilitating technology transactions. Codified technology is easier to patent. Conversely, an increasing appreciation of intellectual property rights encourages codification of innovations.

New technologies are often surrounded by commercial uncertainty (Rosenberg, 1996). Simply put, it is difficult to know what applications the technology can have. This raises the search costs of both buyers and suppliers and leads to considerations of option values rather than actual values, and renders potential transactions subject to a variety of biases that human beings are prone to when faced with uncertainty. The net result is that technology transactions are more imperfect and harder to accomplish.

A special and important case in this context is GPT. Technology trade involving GPT has many of the features that we have just described. There is uncertainty about their applications. Often GPT emerges ex-post, as people realize that a technology created for certain purposes can also be used for other applications. Not only is there uncertainty about the applications but also that the potential users have to invest to learn if the technology is useful to them. For example, Maine and Garnsey (2006) tell the story of Hyperion Catalysis, which has developed special applications of fullerenes, a carbon allotrope discovered in 1985. The firm struggled to find uses for the new materials, and systematically explored applications in a number of industries, including automotive, aerospace, and power generation, through alliances with manufacturers. Today, it produces more than 40 products for these three distinct industries. Thoma (2009) describes a similar process in the case of Echelon, a company that has developed a universal electrical controller technology (LonWork) for diverse applications including a wide range of manufacturing, and heating and cooling systems for buildings.

A common thread running through these examples is that judging the technical merit of the technology or innovation often draws upon a very different set of expertise from that required to judge its applicability to a particular end use. Bresnahan and Greenstein (1996) note that creating new software technology requires expertise in computer science and software engineering. Understanding how the technology can be best used requires not just only the technical expertise, but also management skills and industry expertise. Both are separate, though not independent, sources of uncertainty, which make it significantly more difficult to contract for technology. Nonetheless, there are also significant advantages to specialization with a GPT. As Bresnahan and Trajtenberg (1995) point out, no individual user sector firms will have the cognitive breadth to see the common elements between what they are doing and what firms in other users sectors are doing. Therefore, each sector will not develop the "general" technology. Instead, it will be content to only develop the application of the technology specific to the sector. This is both more costly and also reduces the potential for learning across different applications.

5.2. *Contractual limitations*

Much of the economics literature has focused on the difficulties in writing contracts for technology trade, particularly in contracting for R&D, that is, for technology that is not yet developed (e.g., Mowery, 1983).

Teece (1988) notes three problems associated with R&D contracts. First, because the output of R&D is ill-defined, and hard to predict ex-ante, the parties have to write very detailed contracts specifying several contingencies, raising contracting costs. Second, these contracts call for exchange of information between the buyer and the supplier that they would prefer to keep secret. Third, because of the set-up costs of R&D contracting, or the tight linkages between buyers and suppliers (e.g., because of the need to exchange information), these contracts may be subject to lock-in. That is, once they are set-up, it is hard for both parties to exit the relationship, with implied potential for opportunistic renegotiations. The need to monitor the execution of the contract by the buyer may also require substantial administration costs. But this is like setting up an internal monitoring structure, making little difference between activities that are integrated within the firm, rather than acquired contractually from independent parties. All these factors make R&D contracting particularly costly, thereby encouraging integration of R&D in firms that also conduct the downstream manufacturing and commercial operations.

Zeckhauser (1996) provides a more recent restatement of the problems in contracting for technology in general. In particular, he alludes to problems of asymmetric information and contractual difficulties. He contends that "[c]ontracting to provide technological information (TI) is a significant challenge." Specifically he notes that (i) TI is difficult to count and value and is often sold at different prices to different parties. (ii) To value TI, it may be necessary to "give away the secret." (iii) TI is often bundled into products, such as a computer chip, which reduces efficiency. (iv) The sellers' superior knowledge about TI's value makes buyers wary of overpaying. Notice that most of these considerations apply to many types of modern goods and services, including art and music. Most of the attention in the literature, however, has been focused on the so-called lemons problem, namely that the seller has private information about value.

5.2.1. Asymmetric information and the market for lemons

Arrow (1962) articulated the problem faced by a potential buyer having to pay for information whose value he was unable to judge—the asymmetry in information would introduce inefficiency into the market for technology. Akerlof (1970) showed that this kind of asymmetry in information, plausibly present in the market for used cars, can prevent a market from functioning altogether, as "lemons" drive out good used cars.

The lemons problem in technology trade may not be as serious a problem as some economists believe. Not only are there contracting solutions that can mitigate the problem, in some cases, institutional arrangements may minimize information asymmetries. For instance, in pharmaceuticals, clinical trials reveal a great deal of information about the likely market value of the drug under development. Patents themselves disclose information about the innovation. The lemons problem is probably more serious in international technology transfer, especially between advanced and less advanced countries. In this case, there are barriers to the circulation of information, and a gap in expertise between the two parties. The problem is less severe when both parties operate in the same market or industry wherein technical information circulates, and the levels of technical expertise are similar.

Second, the key assumption of the lemons problem—namely, that the licensor holds useful private information—may not always be sensible. Sometimes the potential licensee may hold more significant private information about the potential applications of the technology. In addition, integrators, such as Boeing or the present day pharmaceutical firms, often embody the in-licensed technology in a larger system, whose characteristics they understand better than others. If so, the buyer may be better able, than the supplier, to evaluate the technology.

Empirical investigation of the lemons problem in licensing is difficult and the few extant studies are from the pharmaceutical sector.[13] Pisano (1997) finds that compounds developed internally are more likely to succeed than in-licensed compounds. Guedj (2005), though not explicitly testing for the lemons effect, finds that projects financed by pharmaceutical companies but developed by biotech firms are more likely to fail than projects developed by pharmaceutical firms. These findings are consistent with in-licensed compounds being drawn from an inferior distribution than those developed internally by the licensee, though other interpretations are also possible. On the other hand, Danzon et al. (2005) find that compounds developed in alliances (roughly equivalent to licensed compounds) have a lower probability of failure in clinical trials. Notice, moreover, that a lemons problem requires that in-licensed compounds be systematically inferior to those that the *licensor* kept for itself. Arora et al. (2009a) develop a structural model of drug development in pharmaceuticals, and find that licensed compounds are drawn from the same distribution as the internally generated compounds of the licensor. Although the empirical literature is both scant and inconclusive, our sense is Lamoreaux and Sokoloff (1999: p. 2) were right when they noted that "... scholars have overemphasized the information problems associated with contracting for new technological developments in the market."

5.3. Patents and the market for technology

Arrow's own solution to the problem of buying a pig in a poke was to appeal to intellectual property protection. If protected, the seller could disclose the details to potential buyers, mitigating the problem. This close relationship between patenting, the market for technology, and specialization in invention is reflected in trends in patenting and measures of the market for technology. Lamoreaux and Sokoloff note that patenting per capita in America rose during the nineteenth century, peaked in the early twentieth century, and then declined thereafter, closely mirroring trends in individual inventorship and in trade in patents. After the mid-1980s, patenting per unit of R&D investment in the United States changed course and began to rise, very close in time to the resurgence in markets for technology as well.

However, know-how and trade-secrets are important complements for patented technology. Robbins (2006) reports that in 2002, the sector NAIC 533 (lessors of nontangible property) earned $7.6 billion from patent licensing in the United States. The firms in this sector are likely pure patent holding companies, or specialized organizations set up by firms in other industries to license patents. Thus, of the $66 billion in technology licensing in the United States, about 12% was accounted for by pure patent licensing and the remainder by technology licensing, comprising patents, unpatented technology, know-how, and technical services.

Arora (1995) shows that patent protection can additionally improve the efficiency of licensing contracts that also require the provision of know-how and technical services, which has been shown to be an important component of licensing contracts (Contractor, 1981; Taylor and Silberston, 1973). He models the case where, along with the technology, the licensor also has to transfer know-how. Given the difficulty in objectively verifying that the know-how is provided, the licensor has an incentive to skimp,

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[13] Evidence for the lemons' problem in financing development of the technology itself is surveyed in Chapter 14, this volume.

since providing such know-how services is costly. Conversely, insofar as some payments are conditional on the provision of the know-how, the licensee has an incentive to withhold payment, claiming inadequate know-how was provided.

The model shows that these problems can be solved by staggering the payment to the licensor over time, and by relying on the property rights on the technology. The buyer's value depends on the technology and the know-how. While the know-how that is transferred cannot be withdrawn, by withdrawing the rights to use the technology, the licensor does have a hostage because the know-how without a license to the patent is of diminished value. In some cases, the bundling with other complementary inputs, such as specialized machinery can provide a similar role (e.g., Arora, 1996). And, as Zeckhauser (1996) notes, technology is frequently sold by embodying in artifacts such as computer chips or software (provided without source code) to overcome the problem.

The empirical literature provides mixed evidence on the relationship between patent protection and technology-licensing contracts. Using a sample of 118 MIT inventions, Gans et al. (2002) find that the presence of patents increases the likelihood that an inventor will license to an incumbent rather than enter the product market by commercializing the invention. Dechenaux et al. (2009) link patent characteristics to outcomes in a sample of 805 MIT inventions licensed to private firms. They find that licenses based upon stronger patents are more likely to be commercialized. Anand and Khanna (2000) find that in the chemicals sector, where patents are believed to be more effective, there are more technology deals, a larger fraction of these are arm's length, involving exclusive licenses and a larger fraction of licensing is for future technologies rather than existing technologies. In contrast, Cassiman and Veugelers (2002) do not find that more effective patents encourage Belgian firms to enter into collaborative R&D arrangements.

Evidence from cross-national data is similarly mixed. Some studies find a positive association between patents and licensing. Yang and Maskus (2001) report a strong positive relationship between improved IPR regimes and licensing by US multinational corporations. Analyzing data on international technology-licensing contracts of Japanese firms, Nagaoka (2002) finds that weak patent regimes are associated with an increase in the fraction of transfers to an affiliate (such as a subsidiary), rather than to an unaffiliated firm. Smith (2001) finds that US firms are more likely to export or directly manufacture rather than license technology in countries with weak patent regimes. A study using French data finds that exports of technology services are greater to countries with more effective patent protection, although only for higher income countries (Bascavusoglu and Zuniga, 2002). Arora (1996) used a sample of 144 technology-licensing agreements signed by Indian firms where the provision of three technical services—training, quality control, and help with setting up an R&D unit—serve as empirical proxies for the transfer of know-how.[14] He found that the probability of technical services being provided was higher when the contract also included a patent license or a turnkey construction contract.

Other studies, however, cast doubts on the link between patent protection and the extent or form of technology licensing. Fink (1997) finds a very weak relationship using German data. Similarly, Fosfuri (2004) does not find that patent protection significantly affects the extent or channel of technology flow (through joint-venture, direct investment or licensing) in the chemical industry. These studies are plagued by the problem of measuring the effectiveness of patent protection, and typically rely upon a

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[14] Mendi (2007) finds that technical assistance is bundled together with the transfer of know-how in Spanish technology import contracts.

widely used index, the Ginarte–Park index, which is based on legal provisions, rather than the actual enforcement of patents. A recent study by Branstetter et al. (2006) exploits changes in patent regimes in countries pressured by the United States. Using detailed data on the technology royalty payments received by US firms, and controlling for country, industry, and firm fixed effects, they find that stronger patent protection does not increase the transfer of technology by US multinationals to unaffiliated parties. However, it does increase the flow of technology to affiliates. Thus, despite much improved measures and a more careful design, this study too reflects the mixed nature of evidence on the topic.

Arora and Ceccagnoli (2006) provide a potential resolution of this mixed evidence. They argue that when licensing is attractive, then patent protection does indeed facilitate licensing. However, for firms with the ability to commercialize technology themselves, patent protection also increases the payoffs to commercialization. Analyzing data from a comprehensive survey of R&D performing firms in the United States, they find that patent protection increases licensing, but only for firms that lack complementary manufacturing capabilities. Hall and Ziedonis (2001) provide similar evidence from the semiconductor industry: all else being equal, small design specialists are more likely to patent, and case study evidence suggests that they do so to license their technologies. Gans et al. (2008) further note that patent licensing occurs predominately during a small time interval, near the date of the patent grant, because a patent resolves some transaction costs in the technology trade, such as uncertainty about the scope attributed to the patent and asymmetric information. Fosfuri et al. (2008) provide empirical evidence that firms that are better protected by software patents are more likely to exchange information in an open source software environment.

The OECD survey by Sheehan et al. (2004) also found that licensing influences patent strategies. They report that firms ranked "revenues from licensing" as the third most important reason for patenting. There are important differences across regions consistent with markets for technology being better developed in North America. First, the importance of licensing in patent strategies is higher for the North-American than European and Asian-Pacific firms. Second, revenue from licensing was mentioned to be very important by 39% of the ICT firms and 27% of biopharmaceuticals firms. A much lower fraction of firms in remaining sectors considered licensing to be a very important motivation for patenting.

In sum, patent protection increases the efficiency of technology-licensing contracts. However, stronger patent protection may also reduce incentives to license in some instances, thereby potentially offsetting the increase in transaction efficiency.

5.3.1. The problem with patents

Some authors have argued that excessively fragmented patent holdings can actually retard the rate at which new technologies are introduced into the market, by encouraging patent holders to hold up innovations in the hope of trying to extract more rents (e.g., Heller and Eisenberg, 1998; Lemley and Shapiro, 2007). They point out that many modern innovations are complex and build upon multiple elements, each capable of being patented separately and independently. When these patents are not held by a single entity, whoever wants to develop the technology needs to collect the rights from the different patent holder, potentially allowing a single patent holder to "hold up" the innovation. Foreseeing this problem, potential integrators may be reluctant to invest in the first instance. More generally, fragmented property rights can potentially lead to a what Heller and Eisenberg (1998) dub "the tragedy of the anticommons" where, instead of no one controlling the use of a common resource as in the well-known "tragedy of the commons," too many people hold a veto (see also Chapter 7, this volume for a more extensive discussion of patent pools and patent thickets).

In a recent study, Cockburn et al. (2008) find that IT firms facing more fragmented IP landscapes have higher licensing costs. In the life sciences, empirical evidence suggests that although patent proliferation has created challenges, it has not as yet become a serious problem, in part because it is possible to work around some of the problems.[15] Walsh et al. (2003) report on interviews with about 70 life sciences companies about the problem, and found that although fragmented patent rights were often encountered, the companies managed to resolve the problem by licensing, working around the patents, or simply by ignoring the problem altogether. Murray and Stern (2007) find that scientific papers see a decline in citations after the associated research is patented, which they interpret as evidence in favor of the anticommons retarding scientific growth. However, a detailed survey by Walsh et al. (2007) of academic researchers in life sciences reported that patents had limited impact on academic research. Only scientific projects with commercial objectives appear to be influenced by patenting by others, which is entirely understandable since existing patents would reduce the commercial, but not the scientific, value of such projects.

However, that the problem can be solved does not mean that it does not exist. Indeed, Merges and Nelson (1990) and Scotchmer (1991) have argued that the short-sighted use of even one patent can impede innovation where a technology is cumulative (i.e., where invention proceeds largely by building on prior invention). Merges and Nelson (1990) relate the case of radio technology where the Marconi Company, De Forest, and De Forest's main licensee, AT&T, arrived at an impasse that lasted about 10 years and was only resolved in 1919 when RCA was formed at the urging of the Navy. In aviation, Merges and Nelson (1990) argue that the refusal of the Wright brothers to license their patent was compounded as improvements were patented by others. Ultimately, World War I forced the Secretary of the Navy to intervene to work out an automatic cross-licensing arrangement. The theoretical literature on cumulative innovation and patent protection is discussed in Chapter 7, this volume.

5.3.2. Patents and nonmarket institutions for technology flows

Technology can also be traded outside the market. In a seminal paper, Allen (1983) describes what he called "collective invention" in the Cleveland district in Britain during the second half of the nineteenth century. During this period, Cleveland saw an active exchange of technical information about blast furnaces. Though many technologies were patented, the firms nonetheless transferred technology and information in meetings and conferences without contracts or royalty payments. Nuvolari (2004) documents a similar phenomenon in the mining industry in Cornwall, in the early nineteenth century. In a series of papers, von Hippel (1987) details instances of information sharing in the late twentieth century as well. He documents active know-how trading networks among engineers working in rival firms in the US steel minimill industry, which managers tolerated because they believed such sharing was broadly beneficial because it enabled their engineers to gain from the experience of others.

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[15] Indeed in Japan, where there are many more patents per product across the entire manufacturing sector than in the United States, licensing and cross-licensing are commonplace (Cohen et al., 2002).

Allen showed that collective inventions depended on mobility of personnel and other channels through which know-how leaked out. Not only was it costly to plug these channels, it appeared that the firms realized that such know-how sharing was mutually beneficial, enabling them to compete against producers in other regions. As Allen notes, know-how sharing was more likely when the higher productivity produced by sharing benefited firms in the region but not firms outside the region. Thus, for example, Nuvolari (2004) notes that improvements in the average aggregate performance of Cornish engines also increased the value of the Cornish ore deposits and that similarly, improvements in the performance of the blast furnaces in Cleveland increased the value of Cleveland iron mines. Second, sharing was likely when problems were common. Indeed, von Hippel (1987) reports that specialty steel mills did not share know-how, because each mill tended to have processes specific to the products it produced. It appears that when the know-how related to proprietary products, it was less likely to be shared, reminiscent of the findings about licensing (rather the lack thereof) in differentiated product industries in Arora and Fosfuri (2003).

The absence of patenting, and of markets in the knowledge more generally, seems important for information sharing. Nuvolari (2004) notes that the collective sharing of technical know-how by steam engineers in Cornwall followed the lapse of the Watts–Bolton patents. Information sharing appears to rely upon barter: In von Hippel's (1987) case studies, managers tolerated and even encouraged the barter of know-how but any attempts to monetize the transactions would surely bring swift punishment. Nonmarket mechanisms for information sharing and diffusion rely upon collectively held norms that can rupture when the market intrudes. Dasgupta and David (1994) discuss the importance of norms of disclosure in governing what they call the Republic of Science. When academic research is also motivated by commercial considerations, the considerations of profit maximization and the academic norms of open disclosure (information sharing) can conflict. Indeed the finding reported by Murray and Stern (2007), that scientists are less likely to cite papers with an associated patent, in conjunction with that reported by Walsh et al. (2007) that academic scientists working to discover drugs (and who intend to file patents on their findings themselves) pay close attention to patents, suggest that commercial considerations can severely erode academic norms. Patents are not the source of commercial considerations but doubtless make them more salient.

Modern day incarnations of collective invention—open source communities—are typically vigilant about enforcing norms. Gambardella and Hall (2006) develop a theoretical model in which sharing norms are unstable when members can use the jointly developed invention to make money, even if members directly enjoy contributing to the joint project. In open source software projects, a mechanism such as a GPL license (which ensures that any software incorporating the jointly developed software must itself be made available under a GPL license) makes deviating from the norm less remunerative, making collective development more likely. In sum, although patents can facilitate trade in technology, they can also undermine the viability of some nonmarket institutions that facilitate the flow of knowledge.

5.4. Contracting for technology without patents

The literature suggests that patents can overcome the potential problem of asymmetric information. However, in a series of papers, James Anton and Dennis Yao show that competition among potential buyers can be leveraged to mitigate the problem as well. Anton and Yao (1994) develop a model in which an inventor cannot obtain a patent and neither can she commercialize it herself. Instead, she must sell the idea to buyers. The problem is that buyers are uncertain about whether the idea is valuable or not. Anton and Yao show that one solution is for the seller to disclose the idea to one buyer. If the buyer does not pay for a good idea, the inventor can credibly threaten to disclose it to the other buyer, thereby destroying some of the rents to the first buyer. What makes the model work is that a potential buyer of an invention values exclusive access to it, which makes eminent sense for ideas or inventions. There is another sense in which Anton and Yao's model is specifically about inputs that are "infinitely expansible" but not nonrival. The Anton and Yao model would not apply, for instance, to a truffle of unknown value. If the only way to determine its value is for the potential buyer to eat the truffle, then the seller cannot credibly threaten to sell it to another buyer if not paid. This paper provides a different but complementary explanation for the importance of a competitive product market for encouraging specialized technology suppliers (see also the discussion of GPT and the importance of product-market competition below).

In a subsequent paper, Anton and Yao (2002) analyze a situation where the invention can be disclosed in parts. Once again, the invention is not patented, and buyers value exclusivity. The value of the invention is conceived of as know-how, whose use increases the probability of successfully using the invention. Buyers do not know the value of the invention, that is, they do not know how much know-how the seller has. Although the "blackmail" strategy is still useful in preventing a buyer from expropriating the know-how, it is not enough. Rather, inventors must now signal the quality of their know-how by partially disclosing it. The better the know-how, the more is publicly disclosed (although more is also left undisclosed because "better" know-how is simply *more* know-how in this model). In order to signal the quality of the invention, sellers must also be willing to have some "skin the game," agreeing in essence to pay the buyer if the invention does not succeed and accepting a share of the payoff if the invention does succeed. Paying the buyer for an unsuccessful invention, or providing a warranty, requires capital, pointing to another link between the market for technology and capital markets. Instances of such warranties are rare, perhaps because successful inventions depend upon the efforts and investments of the buyer, not simply the quality of the idea provided by the seller. Thus, by conditioning the payments the seller receives on successful outcomes provides the right incentives to the seller but also weakens those of the buyer, thereby potentially jeopardizing success of the invention.[16] A warranty by the seller against failure will further attenuate the buyer's incentives to invest, and is probably why such warranties are rare.

5.5. The structure of licensing contracts

The suspected inefficiency of licensing contracts has attracted some theoretical and empirical research. Anton and Yao's work is an example of the application of mechanism design theory to the problem of the market for technology. There is a sizable literature that focuses on the structure of licensing contracts, such as whether licensing contracts are exclusive or not, and whether they have sales royalties or fixed fees, as well as other contractual provisions. A pioneering study by Caves et al. (1983)

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[16] This is a special case of the Marshallian share-cropping problem—unless the inputs are contractible, contracting on output alone is suboptimal (see Cheung, 1968).

documented imperfections in the market for licenses. Gallini and Wright (1990) show that performance-based royalties may allow separation between high-value and low-value innovations, when it is commonly known that a higher value innovation will result in greater output than a lower value innovation (see also Macho-Stadler et al., 1996). Beggs (1992) obtains a similar result in a model in which it is the licensor who lacks information about the "type" of the licensee. Kamien (1992) provides a survey of the theoretical literature.

There are a number of empirical studies on the structure of licensing contracts, mostly based on data from Europe, Brazil, and Japan. This literature shows that the vast majority of licensing contracts involve performance-based royalties, often in combination with fixed fees. For example, Macho-Stadler et al. (1996) found royalty provisions in 72% of 241 Spanish technology transfer contracts while Bessy and Brousseau (1998) found such provisions in nearly 83% of French contracts. Empirical studies of licensing contracts are only weakly related to the theories about the structure of licensing contracts and sometimes yield contrasting findings.[17] Contractor (1981) finds that royalty rates tend to vary very little across licensing contracts for any given industry, and are typically established by "rule of thumb." Nagaoka (2005) analyses Japanese data from the period 1981–1998 across 32 sectors. He finds that high royalties are more likely to be observed when the licensing contract also includes patents. However, Villar (2004) finds that, in a sample of 925 licensing agreements in Spain, the parties are more likely to agree on fixed payments when the technology is patented. More recent attempts to test the insights from contract theory or transaction cost theory to understand the structure of licensing contracts are provided in Bessy et al. (2008) and Brousseau et al. (2007). These studies lack sources of exogenous variation that would identify how observed licensing contracts reflect underlying contract design issues.

6. Consequences of the existence of markets for technology

6.1. The division of innovative labor

One consequence of the existence of well-functioning markets for technology is that they create incentives for vertical specialization. This is just a straightforward application of the classical theory of division of labor. Indeed, as Table 2 shows, in the United States, the revenues of establishments that supply scientific R&D services (NAIC 5417) are sizable: around $75 billion in 2004 and $85 billion in 2005. These establishments are highly R&D intensive, and perform about 5% of the total industrial R&D.

This is consistent with other data reported by the NSF which indicate that contract R&D (the bulk of which was contracted to other companies) grew from 3.7% of total company funded R&D in 1993 to 5.6% in 2003, the latest year for which data are available. The pharmaceutical sector stands out in the extent to which R&D was outsourced, with 13.2% R&D outsourced in 2005.[18] These data clearly point to the substantial specialization in R&D, which is a rough indicator of the extent of what we call the

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[17] In a more recent study, Dechenaux et al. (2009) relate the features of university licensing contracts, such as milestone payments to the special problems in licensing embryonic technologies. Embryonic technologies involve a combination of the need to share risk, discourage the licensee from shelving the technology, and the need to involve the inventor in subsequent development.

[18] See NSF, Science and Technology Indicators (2008). Appendix table 4–51.

Table 2
Estimated total revenue and R&D for US establishments classified in selected service industries in 2004 and 2005
(Billions of current dollars)

		Revenue		Total R&D	R&D as % of total industrial R&D	R&D/sales
Service industry	NAICS code	2004	2005	2005		
Professional, scientific, and technical services (except Notaries)	54	966	1058	32.0	14.2%	3%
Scientific R&D services	5417	74.8	81.5	12.3	5.4%	15%
R&D in physical, engineering, and life sciences	54171	70.0	76.4			

Source: Science and Engineering Indicators 2008, tables 2, 4–20, NSF 07-335.

division of innovative labor. It is also likely that the United States is in the vanguard of this trend. Comparable data, if available, would likely show a less extensive division of labor in Europe and Japan.

Consistent with the rise of technology specialists, large firms account for a steadily smaller fraction of R&D performed in the United States. Figure 4 shows that the share of nonfederal R&D accounted for by large firms, defined at those with more than 25,000 employees, has fallen steadily from around two-thirds in 1980 to slightly more than one-third in 2005. Over the same period, small firms, defined as those with fewer than 500 employees, have increased their share from 6% to around 18%. Firms in the next size category (500–999 employees) have seen a similar increase. Doubtless this reflects changes in the industrial structure in the United States, but it also points to the growing ability of small firms to appropriate rents from innovations, perhaps through the licensing to others.

This type of specialization reflects the tendency toward progressive specialization as markets expand. George Stigler had argued that when an industrial activity, such as the production of new technology, has large fixed costs, restricting the provision of that activity to a single specialist producer who can serve the entire market will yield the greatest economies of scale (Stigler, 1951). However, the various imperfections in the market for technology imply that the cost of acquiring external technology must be counted against the potential benefits of specialization. Intuitively, the benefits of specialization increase with the size of the market, but as Bresnahan and Gambardella (1998) point out, the size of the market for the technology specialist is different from the size of the market for the product. They show that the relevant size of the market for technology is the number of different applications or buyers (breadth) rather than the intensity of demand of the average application. Simply put, a large firm can produce technology more cheaply than acquiring it externally, once the cost of adapting external technology is included.

Bresnahan and Gambardella (1998) develop a model with several downstream firms which do not compete (and thus can be thought of as downstream applications) and one upstream supplier of technology. Downstream firms can either develop a dedicated technology or buy from the technology supplier. Technology development requires a fixed cost, and technology developed by a downstream firm can only be used internally. On the other hand, the technology of the upstream supplier is a GPT applicable to all downstream firms, but it needs to be adapted at a cost which increases with the intensity

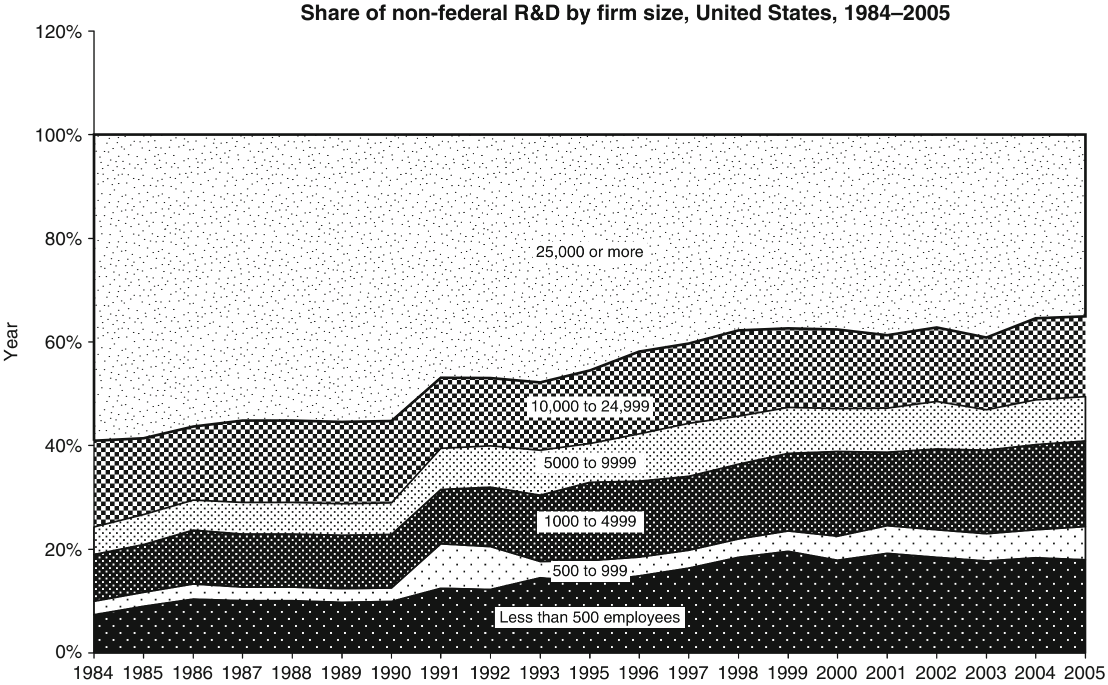

Figure 4. Share of Nonfederal R&D by Firm Size, United States, 1984–2005. Source: NSF Science and Technology Indicators, various years.

of use. Thus, downstream firms with greater intensity of demand (i.e., “large buyers”) develop dedicated technology, whereas smaller firms buy the GPT. A crucial insight is that as an existing market is divided among a greater number of producers, the benefits of a division of labor grow. As a result, firms that were hitherto producing technology internally may switch to buying. By increasing demand for the technology supplier, this type of market broadening also encourages the supplier to invest in making the technology more general, reducing the cost of adaptation. Gambardella and Giarratana (2009) find that division of innovative labor and the generality of technology go hand in hand: Specializing as a technology supplier is more attractive when the technology is more general purpose.

Arora et al. (2009b) test the predictions of Bresnahan and Gambardella using data from the chemical plant engineering sector. In their model, large chemical firms (those investing in more than one plant) choose whether to design the plant internally or engage an external supplier of design and engineering services, labeled SEFs. Small firms either use an SEF or do not enter the market. They generalize the model by allowing the number of SEFs operating in a market to depend on the demand for their services, and therefore depend upon the decisions of potential buyers, that is, the chemical firms. Consistent with the theoretical predictions in Bresnahan and Gambardella (1998), they find that the number of SEFs increases when the market expands through an increase in the number of potential buyers but not when market expansion is due to an increase in the average size of buyers.

6.2. Entry and competition upstream and downstream

Markets for technology enhance entry and competition in both the upstream technology supplier industry and the downstream product industry.

Without markets for technology, a company that can develop a new technology will be unable to enter the market, unless it also able to invest in the far more costly and risky assets to develop and commercialize the innovation. Both Table 2 and Figure 4 show the increasing role of small firms and technology suppliers in the innovation system in America. Notice that the resurgence of the market for technology coincides with the increasing importance of R&D services suppliers and small firms. It also coincides with the boom in patenting in the United States, reversing a long period of decline. Figure 5 shows that after falling steadily from the 1960s, US patent applications per R&D dollar reversed trend in the mid-1980s. As discussed, patents enable the technology specialists to appropriate the rents from their innovations (see Hall and Ziedonis, 2001 for semiconductors, and Cockburn and MacGarvie, 2006, for software).

In the United States, specialized intermediaries, such as Royalty Pharma, buy future royalty streams from licensed inventions from small firms and universities, bolstering the ability of inventive firms to sustain themselves without having to participate in commercialization. Thus, while patents are often seen as an instrument for restraining competition, they have features that may also enhance it. Hall and Lerner discuss the role of patents in financing innovation in Chapter 14, this volume in greater detail.

In addition to facilitating the entry of technology specialists, technology markets also stimulate entry and competition in the downstream product markets. The availability of technology lowers entry costs into the product market, particularly for firms that lack internal R&D capability for innovation or even

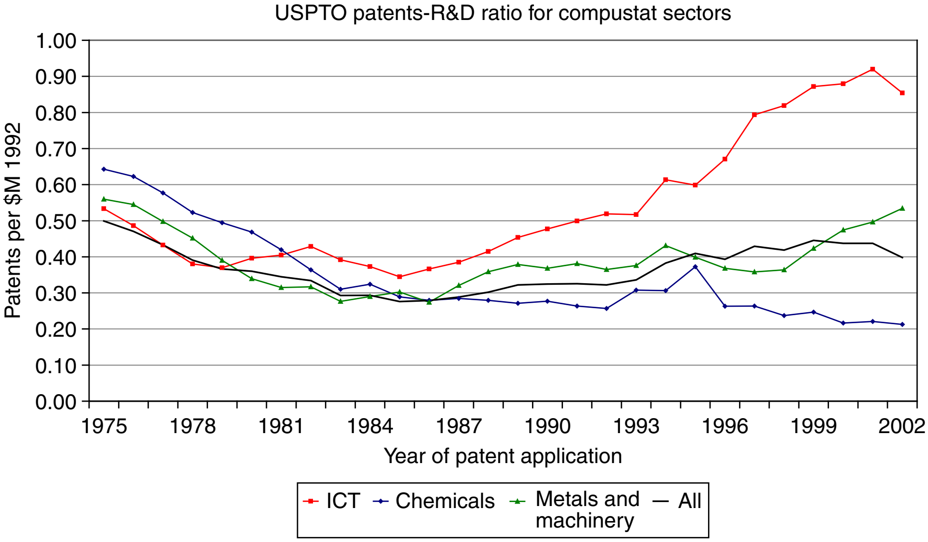

Figure 5. US patents per million dollars of R&D, 1975–2002. Source: Bronwyn Hall, private communication.

quick imitation. Moreover, specialized technology suppliers have an incentive to offer complementary services and know-how, and to reduce the cost of absorbing and using the technology.

The impact of licensing on entry is evident in the chemical industry, which has a long history of licensing of chemical processes (Arora and Gambardella, 1998). Lieberman (1989) finds that licensing was less common in concentrated chemical products, and that when licensing was restricted, there was less entry. In a related study of 24 chemical product markets, Lieberman (1987) reports that patenting by outsiders was associated with a faster decline of product price, once again suggesting that patenting by outsiders encouraged entry in the product market. Arora et al. (2001b) provide more direct evidence that specialized technology suppliers facilitate downstream entry. Using data on the chemical plants built during the 1980s in 38 less developed countries (LDC), they find that the number of specialized suppliers (SEFs) increases both the total number of plants in a market (a country sector pair), as well as the fraction that are based on externally supplied technology.[19] Simply put, a market for technology enhances competition downstream by making technology available more broadly and cheaply, enabling the entry of firms that would not enter otherwise.

By making technology less scarce, technology markets reduce the value of technology as a critical competitive asset. Competitive advantage must be sought in other assets, which are located downstream. Thus, firms try to differentiate products created with similar and relatively widely available technologies. The ability to create a specific product or market niche then becomes critical for success. Consistent with this, Arora and Nandkumar (2007) find that in the information security software industry, technology markets raise the value of marketing capabilities in ensuring the survival of firms, while diminishing the value of technical capabilities.

The discussion in this section also highlights that a division of innovative labor is a mechanism for creating spillovers that are transmitted to other parts of the system via the upstream sector of technology suppliers (see also Bresnahan and Trajtenberg, 1995). In brief, positive shocks to downstream industries (e.g., an increase in demand or the development of complementary technologies) induce positive shocks upstream (e.g., higher productivity or new technologies), which are then transmitted to the other downstream sectors served by the technology supplier industry. The link between two seemingly unrelated downstream sectors occurs because the shock to one sector raises the productivity of the upstream sector which then enhances the productivity of the other sector to which it is applied. For example, growth in the first world chemical market gives rise to specialized technology suppliers, the SEFs, which subsequently supplied LDC markets, contributing to the growth of the chemical industry. The link with the upstream SEF is key for transmitting the shocks from one product market to the other.

Importantly, these spillovers can also occur across sectors. In his study of the US machine tool sector in the nineteenth century, Rosenberg (1976) noted that the various downstream industries using machine tools arose at different times. For instance, firearm manufacturing emerged earlier than sewing machines, typewriters, or bicycles. The growth of the firearm industry spurred the development of

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[19] Conversely, in Klepper's (1996) model of industry shake-outs, a key entry barrier is new firms' inability to enter by innovating. The returns to process innovation are proportional to size, and entrant size is eventually too small compared to incumbents. A market for technology would enable process specialists to enter with process innovations, although other features of the model would imply that downstream producers would still face rising barriers to entry over time.

metal cutting and shaping machines. Bicycle production required metal cutting operations that were very similar to those of the firearm industry (e.g., boring, drilling, milling, planning, grinding, polishing, etc.—see Rosenberg, 1976: 16), and thus the bicycle industry could rely upon the suppliers of metal cutting machines that were already serving the larger firearm industry. What the suppliers had learned in producing metal cutting machines for the firearm producers did not have to be learned again to supply bicycles producers. The commonality in the learning process across the industries, or what Rosenberg called "technological convergence," was critical for the transmission of growth, but required the intermediation of an upstream sector.

6.3. The rise and decline and the rise once again?

Recall that Lamoreaux and Sokoloff had documented an extensive market for technology in the United States in the nineteenth century, which declined by the end of the century. By World War II, innovation in the United States was dominated by the in-house laboratories of large corporations, a trend that continued well into the 1960s. Data discussed earlier indicate that the market for technology has revived, certainly by the beginning of the 1990s, and likely somewhat earlier. Mowery (1983) and Teece (1988) argue that increasing contracting problems, principally due to asymmetric information, undermined the market for technology in the nineteenth century.

Lamoreaux and Sokoloff (2005) take issue with this view. Instead, they argue that the market for technology in the United States in the nineteenth century was closely related to the existing division of innovative labor between independent inventor-entrepreneurs and manufacturers who relied upon them for inventions and improvements. Thus, the decline of the market for technology is, in their view, rooted in the decline of the individual inventor. Individual inventorship declined, in turn, because invention became increasingly rooted in science and engineering, rather than practical experience alone. In their sample of prolific patentees, their so-called "great inventors," they find a marked increase in the educational attainments of inventors born after 1865. They further argue that this increasing technical education requirement must have limited entry into independent invention, resulting in a situation where inventors either had to seek employment with large firms, or commercialize their inventions themselves, although on a much larger scale than before. Raising large amounts of capital was difficult, especially for inventors without an established track record. Thus, larger firms with superior access to national capital markets had a marked advantage in financing innovation. In other words, Lamoreaux and Sokoloff (2005) suggest that a combination of increasing cost of R&D and contracting problems in the capital market rather than in the market for technology were behind the decline of the market for technology in the nineteenth century.

Aghion and Tirole's (1994) model also rationalizes a capital-constraint story. In their model, both the buyer and seller (the R&D unit, in their exposition) provide inputs that contribute to a successful invention. They show that when the seller's inputs are noncontractible but the seller is cash constrained, the buyer may end up in control, even when it would be more efficient to give control to the R&D unit. Thus, financial constraints may limit the division of innovative labor. Lerner and Merges (1998) provide evidence from biotechnology licensing and R&D contracts to show that control rights tend to favor the buyer, who is also financing the R&D, when the financial position of the R&D performing firm is weak.

Our discussion suggests a complementary explanation, which appeals to the changes that were taking place on the demand side. The early twentieth century was also a time of significant market integration, leading to the rise of the great Chandlerian firms. At a minimum, this consolidation in production, even while accompanied by growth in population, would lead to deeper, rather than broader, markets for a potential technology supplier. Following Bresnahan and Gambardella (1998), this would imply lower gains from specialization in technology supply. Indeed, in their empirical study of the division of labor in the chemical engineering sector, Arora et al. (2009b) find that as the share of large firms in a market increases, fewer small firms enter, resulting in fewer specialized suppliers. Note that the Anton and Yao (1994, 2002) theory yields a similar prediction: a reduction in competition among potential buyers reduces the ability of the inventor to appropriate rents from her invention, thereby reducing the number of innovators.

The resurgence of markets for technology in the 1980s can be explained by the same set of factors. The tremendous growth in the scope and sophistication of capital markets, particularly for financing young, technology-based, ventures, surely helped mitigate the challenges that entrepreneurial inventors faced. Equally, the growing science and engineering basis of technical change, along with an accommodating public policy, improved the efficacy of patent protection. Arora and Gambardella (1994a) argue that improvements in instrumentation (particularly information technology) strongly complemented the use of scientific knowledge, contributing to a greater tradability of knowledge, and also increased the scope of new technologies.[20] Furthermore, changes in the composition of industrial activity have broadened the potential market for technology, complementing the greater generality of innovation, which would favor specialized suppliers of technology.

These considerations also suggest that the United States, with its long tradition of widely accessible patent protection, especially for small inventors, would provide more hospitable environment for a market for technology to thrive. However, other than Khan and Sokoloff's comparison of costs of patenting in the nineteenth century Britain and the United States (Khan and Sokoloff, 2004), we are not aware of any systematic studies on why markets for technology have not grown as vigorously outside the United States.

7. Conclusions and avenues for further research

Despite the many challenges it faces, trade in (disembodied) technology has grown steadily over the last two decades, and is now sizable. Its extent and spread has been uneven, both across regions, and across industries. With some exceptions, there is little known about what factors condition the extent of markets of technology and how these vary across industries and technologies, or across space and time. Explaining this variation is an important opportunity for further research.

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[20] After examining a variety of political economy explanations, Kortum and Lerner (1999) conclude that the spurt in patenting in the United States after 1984 cannot be attributed to policy changes, such as the establishment of the Court of Appeals of the Federal Circuit. Instead, they suggest that a broad based increase in research productivity, as well as changes in the management of research, is a more likely explanation. However, Hall and Ziedonis (2001) show that the increase is partly due to patent portfolio races in the semiconductor sector whose cause was rooted in the increased strength of patents induced by the early 1980s policy changes.

At the risk of oversimplification, the focus in the literature has been on the transaction, and on the costs of the transaction relative to alternatives. There has been much less on the broader context of the transaction, conforming to the view in which transactions in technology are *ad hoc*, the exception rather than the norm. The steady growth in the volume of trade in technology makes it important to understand the market for technology, not simply the particularities of the transactions.

A particularly important aspect of the market for technology is the growth of firms that specialize in supplying technology. The determinants of a division of innovative labor (including the nature of technology), the conditions of intellectual property protection, and the industry structure in the product market, are all important topics of further research. The special role of GPT in the innovation process alerts us both to the potential importance of a division of labor and to the potential perils of studying an industry in isolation from where it draws its inputs, including technology.

Another potentially fruitful area for additional research is how the internal organization of firms interacts with markets for technology. Although there are some prescriptions offered in management books (e.g., Chesbrough, 2003), an analytical and empirical exploration of how the internal organization of firms conditions their participation in the market for technology, and conversely, how markets for technology are likely to affect how firms are organized, and in particular, how R&D is managed inside firms.

The most glaring lacuna is probably on the consequences of markets for technology, particularly for growth in productivity and for industry structure. Most economists would agree that trade is mutually beneficial, that it improves resource allocation and increases efficiency. Easing the conditions for trading industrial inputs, such as technology, should have important and measurable effects. The few studies reviewed here suggest that they lower entry barriers and increase competition. Scattered evidence from the literature on international technology diffusion (see Chapter 3, Vol. 2) also points to potential impact on productivity growth, although the evidence is mixed and the role of technology trade in that is even less clear. A systematic examination of how markets for technology affect the rate and direction of inventive activity is therefore urgently needed.

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